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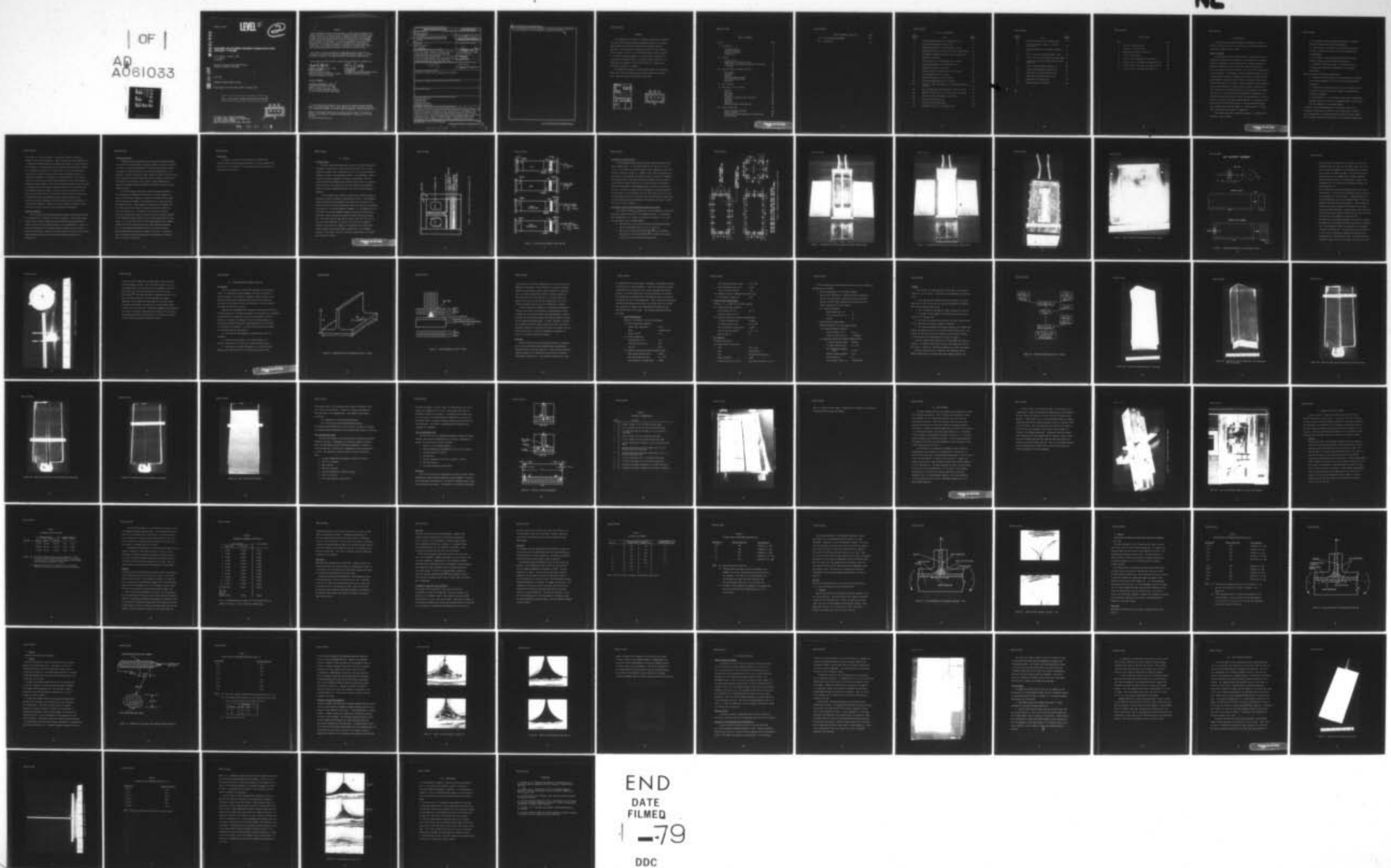

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DEVELOPMENT AND ELASTOMERIC PROCESSING OF WOVEN GRAPHITE/EPOXY STRUCTURAL "T" SECTIONS

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R. T. Achard
R. Rolfes

Advanced Structures Development Branch
Structural Mechanics Division

July 1978

TECHNICAL REPORT AFFDL-TR-78-88

Final Report for Period March 1976 to January 1978

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This technical report has been reviewed and is approved for publication.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This program applied woven and unidirectional graphite/epoxy prepreg to the fabrication of spar-to-wing-cover joint concepts that are integrally cured. The program screened and developed the root area filler for these elements, such that crack formation, growth, and ultimate failure would not occur in this critical region. Results indicated that a rolled, layered composite root filler using glass scrim cloth and a staged commercial film adhesive with carrier provided adequate strength in the root area. A reticulated foam filled elastomeric tool was demonstrated to be both practical and of low cost in

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fabricating quality structural specimens. This tool technique is considered to be both practical and cost effective in a production situation.

FOREWORD

This program was initiated to investigate fabrication techniques and empirically determine design configuration details for integral-spar-to-wing-cover concepts fabricated from advanced composite materials. The program was conducted by personnel in the Composites Facility Group with Capt. C. D. Shirrell acting as project engineer, R. L. Rolfes as design engineer, E. C. Klein and W. H. Leisler as fabrication technicians, and R. T. Achard as project director. The manuscript was prepared by Capt. Shirrell and R. T. Achard, with typing and layout by C. S. Hardin.

The program was primarily conducted between March 1976 and March 1977, with a final testing and analysis phase conducted in January 1978. The final report was released in May 1978.

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I. INTRODUCTION

This introduction presents background information relating to technical factors that formed the basis for the structural/fabrication development program reported herein.

Composite Tooling

Constrained elastomeric tooling (CET) is a useful and typically inexpensive technique that is applied to the fabrication of composite structural components. This procedure used the thermal expansion of elastomeric mandrels that are constrained within a rigid frame to apply consolidation pressure during the cure cycle of the thermosetting plastic components. For example, a basic arrangement employed to cure a graphite-epoxy structural component might consist of shaped (molded) rubber mandrels, metallic locator structure, separators, and optional bleeders and metallic caul sheets. These components would be assembled within a rigid metallic or ceramic fixture, having an internal mold line contoured to the desired exterior of the structural article being fabricated. The fixture would be instrumented for temperature, and possibly pressure, and located in an air circulating furnace. With the application of heat, the rubber mandrels expand at a rate greater than the metal box and thus apply pressure to the uncured graphite-epoxy part, causing resin bleed and compaction. Simultaneously, the epoxy resin cures under the influence of temperature.

This process has several attractive benefits. As summarized in Reference 1 these include:

1. The internal pressure eliminates the need for expensive and time consuming autoclave curing equipment.

2. Multiple parts can be made from the same tooling without the time consuming and failure prone tasks associated with vacuum bagging.

3. The tooling is often uncomplicated and may be readily modified, without extensive machining operations.

4. Elastomeric tooling may result in a simplification of the structural component and minimization of machining requirements.

However, CET has the following disadvantages:

1. Temperatures and pressure are not individually controllable, as are often necessary for the cure cycles of graphite-epoxy structures.

2. Fabrication of elastomeric molds can be very difficult when they are to be used to manufacture complex three-dimensional structural components.

3. The properties of the elastomeric molds, such as dimensional stability and the coefficient of thermal expansion, are not static but they change with the repeated useage.

In practice, these "disadvantages" can be partially overcome by externally controlling the pressure on the tooling rubber. However, this technique must be judiciously applied since most tooling rubbers do not transmit pressure hydrostatically, even at elevated temperatures.

Thus, there is a strong tendency to nonuniformly apply the compaction pressure to the uncured component. Under a recent AFFDL study (Reference 2), a controlled internal pressure CET technique was proven to be both practical and economical. The elastomeric tools constucted for that program consisted of an elastomeric bladder with a central void. This void was externally pressurized to generate precisely the desired part pressure, which was, therefore, independent of temperature. Pressures applied in the void by a regulated air source were fairly evenly transmitted to the mold through the elastomeric rubber bladder. The tool was successfully used in the fabrication of subscale wing sections having integral spar-to-lower-cover joints, some with embedded metallic sections. The upper cover was concurrently cured within the contoured fixture in the same run with the lower cover and spars. In common with many other molding processes, skillful design of the controlled pressure elastomeric tooling is essential for the fabrication of a satisfactory component. However, controlled pressure elastomeric tooling does allow for minor error that would otherwise be unacceptable.

Composite Materials

Woven and unidirectional graphite/epoxy prepregs are emerging materials in the manufacture of aerospace structural components. Woven graphite/epoxy prepreg offers economic savings over unidirectional prepreg by minimizing prepreg lay-up time and by simplification of ply configurations. However, it has the disadvantage of a decreased strength-to-weight ratio over that of unidirectional prepreg. Hybrid structures using both woven and unidirectional graphite/epoxy prepreg may offer acceptable mechanical properties at minimum costs.

Structural Concepts

Programs are being sponsored by the Structural Mechanics Division of the Air Force Flight Dynamics Laboratory (AFFDL) to design and analyze the costs and structural performance of advanced integral spar conepts, comparable to those of Reference 2, for aircraft wing structures. In addition to stresses produced by flight loads, the integral spar structures may be subjected to internal pressures from fuel storage. Other factors influencing the durability of the structure include degradation of mechanical strengths caused by absorption of moisture and fuel into the composite matrix.

An in-house design, fabrication, and test program (Reference 3) was undertaken by the AFFDL to develop data on the effectiveness of various "T" structural elements to resist fuel pressure induced loads. These elements were designed as the intersection of a wing spar with the wing lower cover. Some concepts in this study were designed with the inside plies of the wing cover being turned at right angles to form the spar web plies. In support of this program, screening tests were considered necessary to develop the filler material required at the triangular shaped junction of the two spar angles with the wing cover; i.e., in the fillet area. It was hypothesized that the complex loading in this area would require a root with transverse strength; e.g., as provided by random chopped fiber or an oriented fibrous material adding multidirectional strength to the resin. In addition, metal tooling and autoclave pressurization were employed to fabricate the test coupon in that effort.

Program Goal

A program, to screen the root material of integral spars using low cost controlled pressure elastomeric tooling, combined with the low cost lay up inherent to woven materials, was conceived and is documented in this report.

II. TOOLING

Tooling Concept

The basic premise underlying the action of the controlled pressure elastomeric tooling used in this study was the transfer of a uniform compaction pressure from a regulated air source to an uncured composite component by means of an elastomeric bladder. The elastomeric bladders, an uncured composite component, two metal tooling plates, and other related fabrication materials were confined inside a metal box, Figure 1. The metal box was then placed in an oven and heated to approximately 250°F, the gelation temperature of the resin in the uncured composite component.

At this temperature, a 100 psi pressure was introduced inside the elastomeric bladder by means of a regulated air source. The elastomeric bladder hydrostatically transferred this pressure to the walls of the metal box and to the metal tooling plates which then uniformly transferred the pressure to the uncured composite component. At the beginning of the 250°F dwell the uncured composite component was quite fluid and easily compacted, thereby allowing the removal of excess resin and entrapped air. The temperature was then slowly raised to 350°F and held for two hours at 100 psi pressure. At the end of the period the composite component was fully cured. Figure 2, illustrates this curing process and the changes that occurred inside the metal box. The following sections in this report describe in detail the fabrication of the metal and elastomeric tooling.

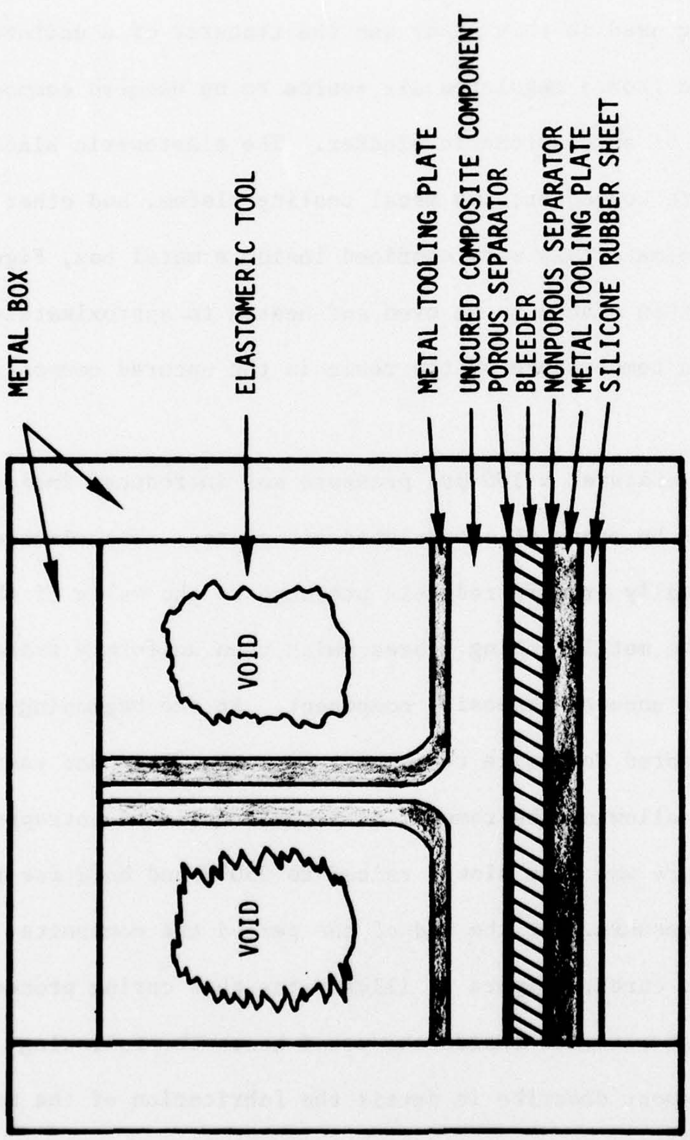


Figure 1. Cross-Sectional Drawing of the Elastomeric Tool

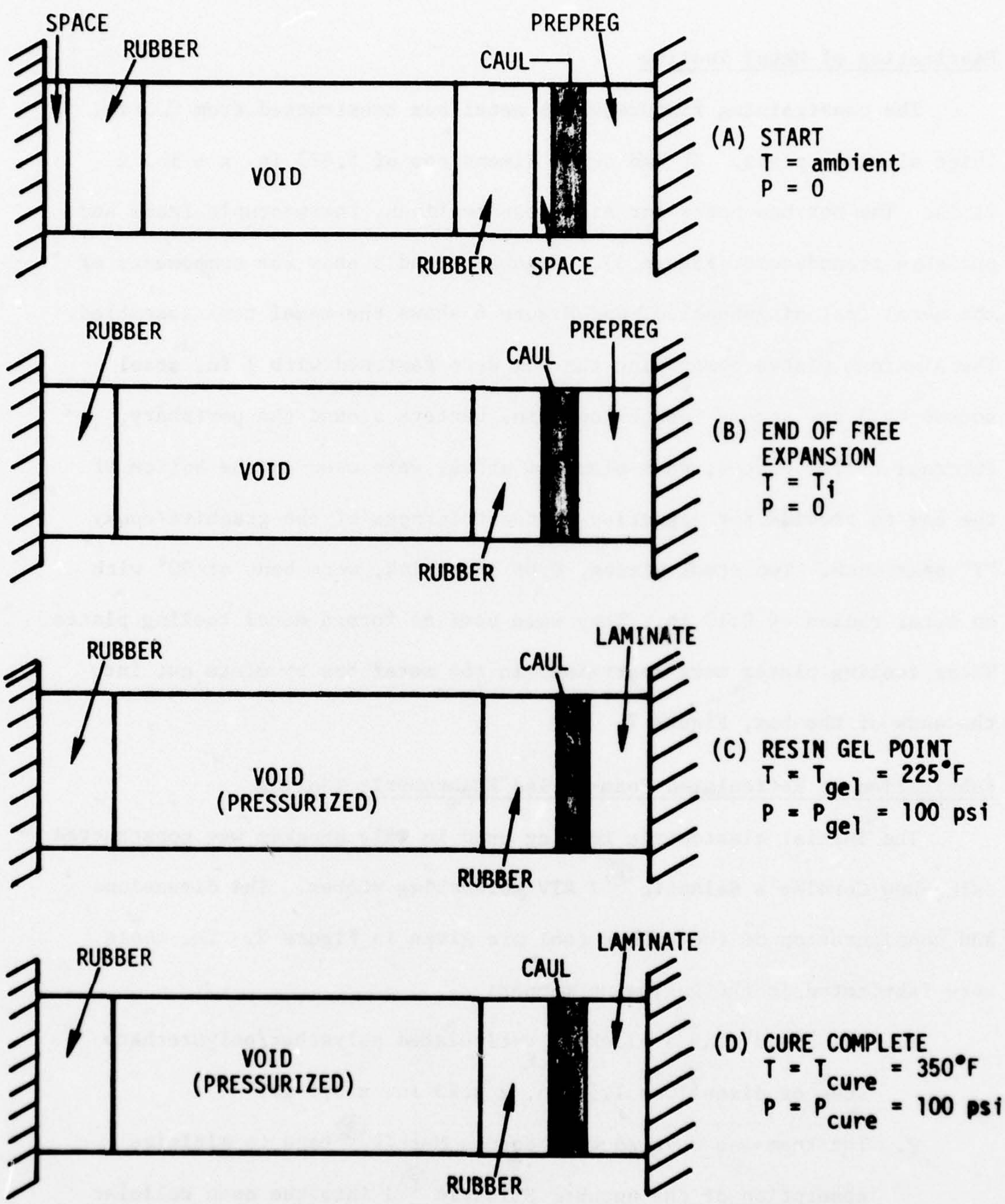


Figure 2. Curing Process/Changes Inside the Box

Fabrication of Metal Tooling

The constraining fixture was a metal box constructed from 0.5 in. thick aluminum plate. It had outer dimensions of 5.875 in. x 6 in. x 13 in. The box has ports for air pressure lines, thermocouple leads and pressure transducers (Figure 3). Figures 4 and 5 show the components of the metal tool disassembled, and Figure 6 shows the metal tool assembled. The aluminum plates comprising the box were fastened with 1 in. steel socket head cap screws located on 2 in. centers around the periphery. Internal filler plates, thin aluminum stock, were used in the bottom of the box to provide for variation in the thickness of the graphite/epoxy "T" spar base. Two steel plates, 0.06 in. thick, were bent at 90° with an outer radius of 0.19 in. They were used as formed metal tooling plates. These tooling plates were restrained in the metal box by slots cut into the ends of the box, Figure 7.

Fabrication of Reticulated Foam-Filled Elastomeric Tooling

The initial elastomeric tooling used in this program was constructed using Dow Corning's Silastic® J RTV moldmaking rubber. The dimensions and configuration of the rubber tool are given in Figure 8. The tools were fabricated in the following manner:

1. The "void" was a block of reticulated polyether/polyurethane foam of dimensions 1.50 in. x 4.25 in. x 9.0 in.
2. The foam was covered with Borden Mystik® tape to minimize absorption of the uncured Silastic® J into the open cellular structure of the polyether/polyurethane foam.

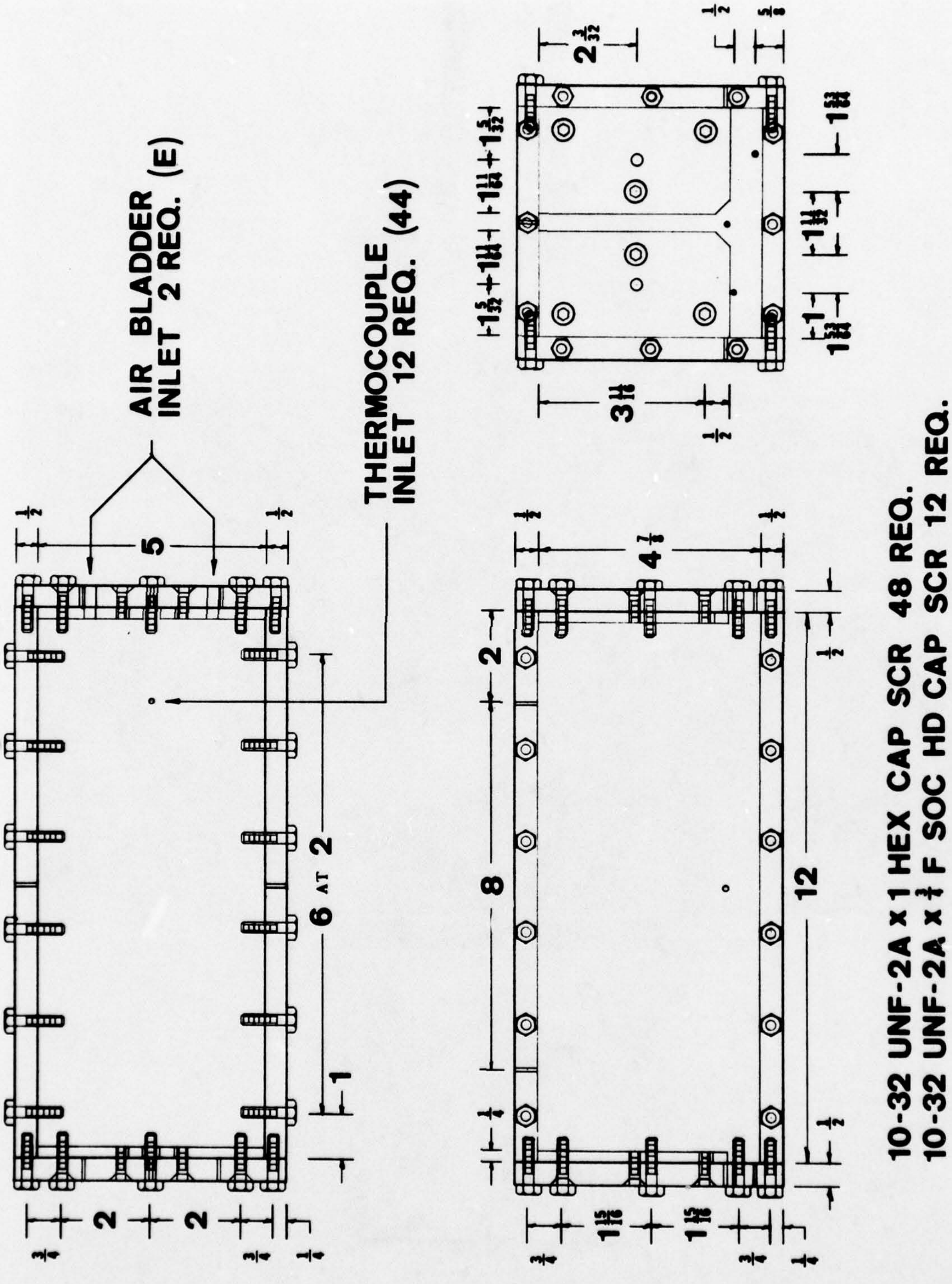


Figure 3. Engineering Drawing of the Elastomeric Tool Box

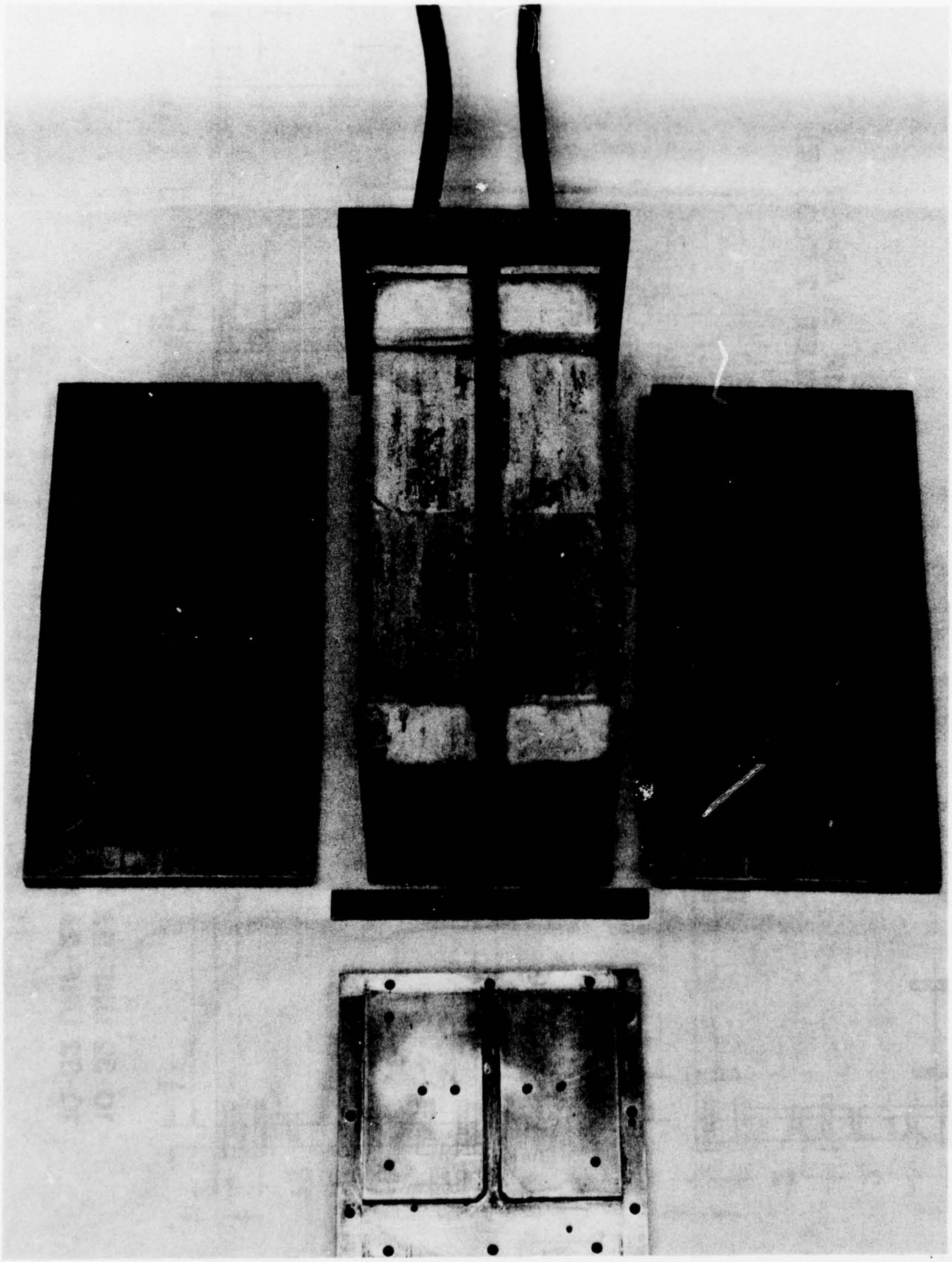


Figure 4. Unassembled Tooling Box Without the Metal Forming Plates

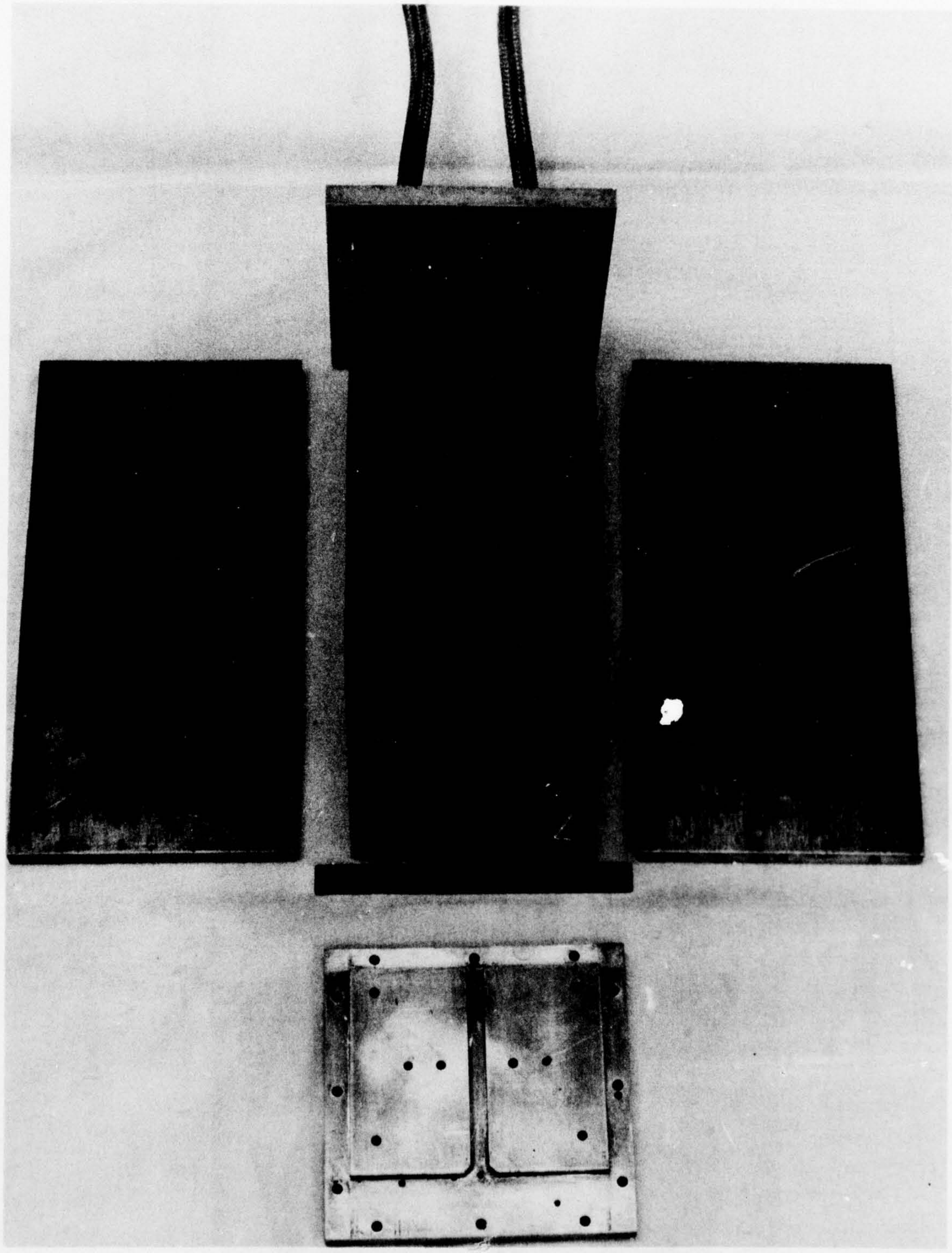


Figure 5. Unassembled Tooling Box With the Metal Forming Plates

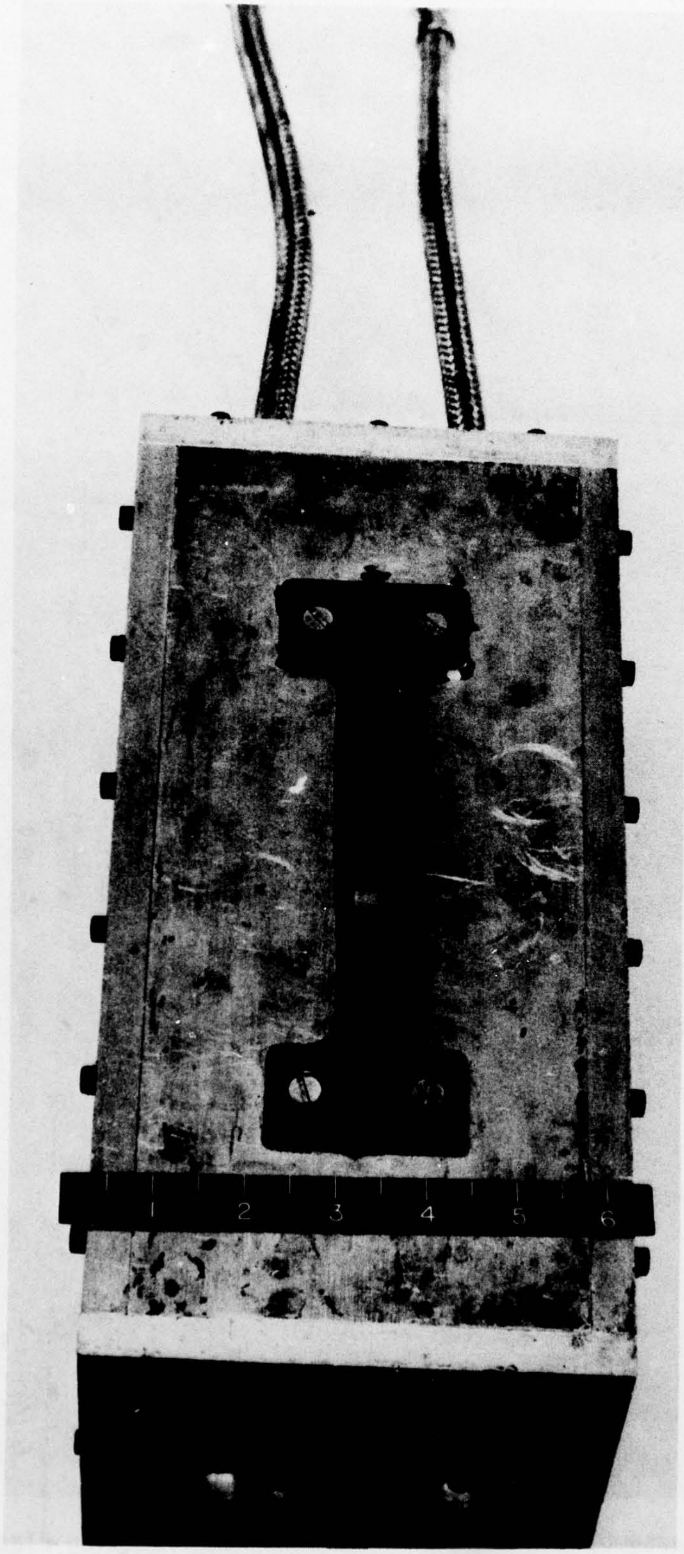


Figure 6. Assembled Tooling Box

Figure 7. Metal Pressure Plate Restraining Slots - Bottom

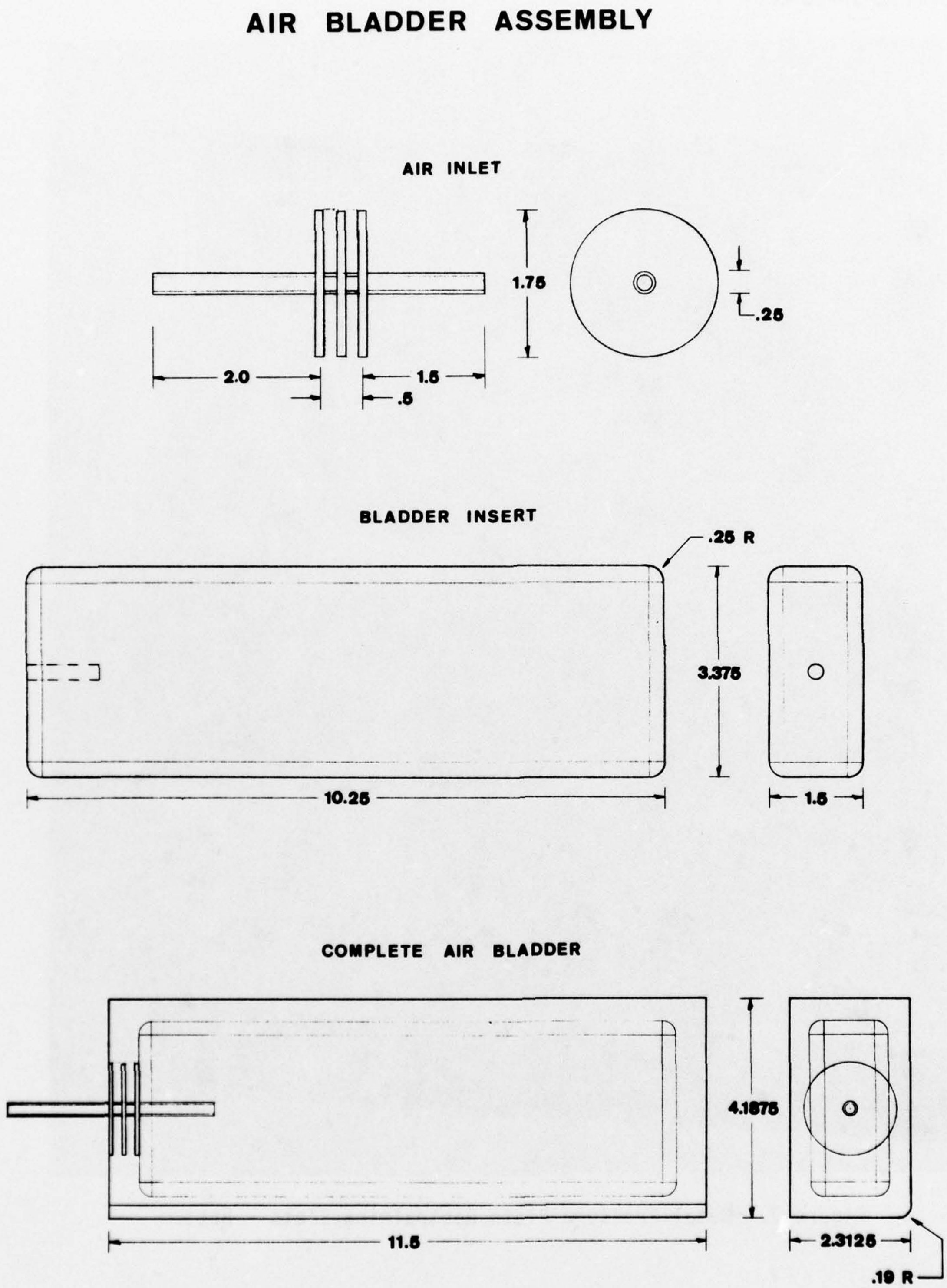


Figure 8. Engineering Drawing of the Elastomeric Tools

3. Figure 8 shows the dimensions of the brazed air entry tube assemblies that were cast into the rubber tools. Two of the steel collars are embedded in the elastomer wall to prevent pull-out and to minimize air leaks. The third steel collar mounts flush with the aluminum wall to prevent elastomer extrusion through the port of the metal box. Figure 9 is a photograph of a two-collar unit used towards the end of the program (Section VI).
4. The air lines were inserted through the ports in the wall of the metal box. The metal box was assembled leaving the end of the box opposite the air ports open. A dummy specimen with the final dimensions of the cured graphite/epoxy "T" spar was bonded to the formed metal tooling plates. This assembly was inserted into the box along with the necessary metal filler plates and bleeder materials. The reticulated foam blocks were lowered into position inside the metal box such that the end of the metal air line extends 2.0 in. into the foam.
5. The metal box with the dummy specimens, filler plates, bleeder materials, and reticulated foam blocks were used as a moldmaking form. The elastomeric rubber was poured into the remaining cavities of the metal box. It was poured in two operations so as not to buoy or compress the foam by the hydraulic head developed by the column of heavy fluid. The rubber was first poured to a depth of 2.25 in., such that the collars on the air

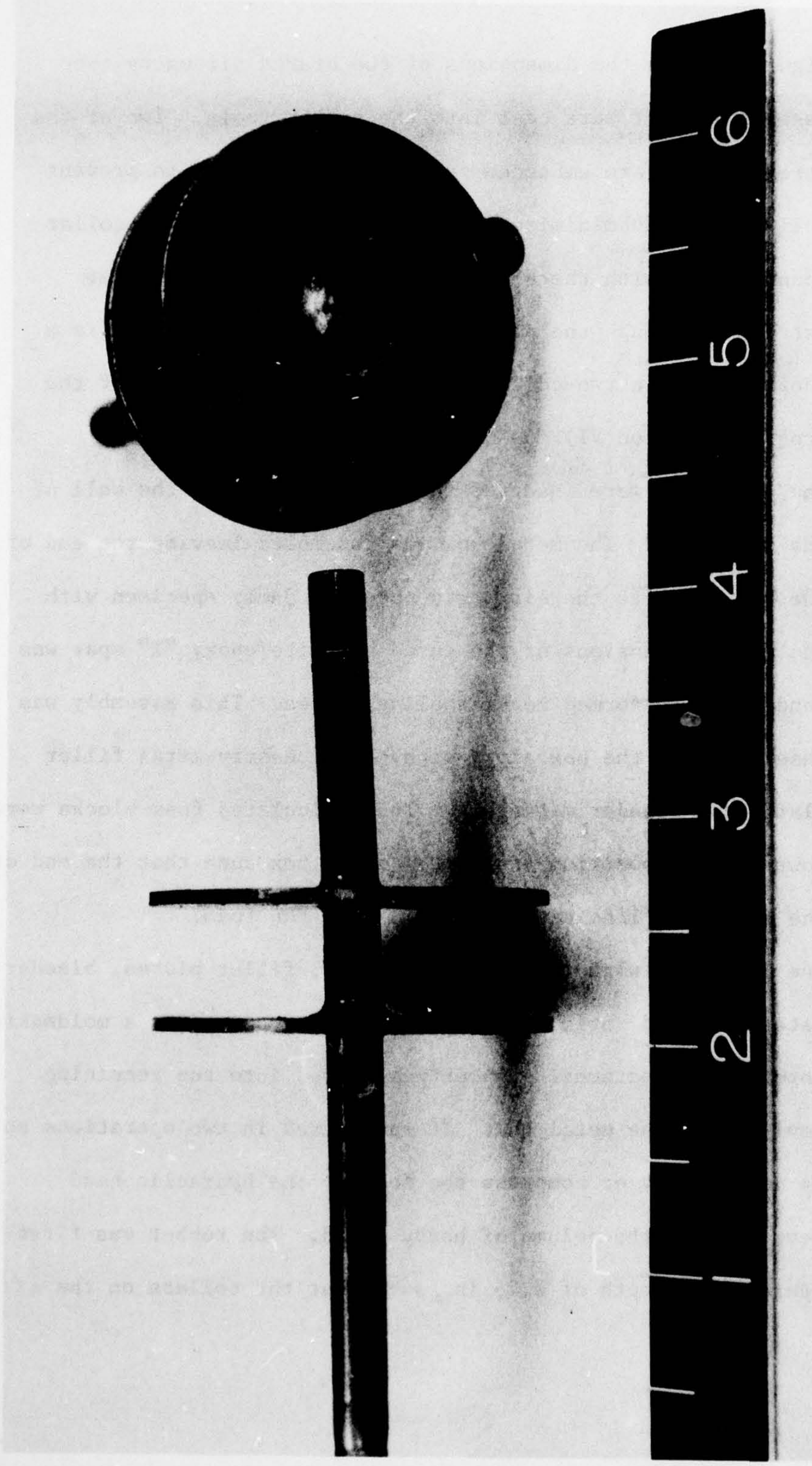


Figure 9. Elastomeric Tool Air Entry Tubes

lines were fully covered and the bottom edge of the reticulated foam was slightly covered. This section was allowed to cure at room temperature for 24 hours and then the remainder of the tool was poured. The tool was then allowed to cure for 48 hours.

6. The Silastic® J RTV rubber was made by combining one part of the base resin with ten parts of the curing agent (by weight). Immediately after mixing the curing agent with the base rubber, the mixture was deaired by placing it in a vacuum chamber under a vacuum of 29 in. of mercury. The material expanded to approximately four times its original volume under the influence of the vacuum. This debulking process was continued for five minutes after which the RTV rubber was poured as described in Step 5.

III. SPECIMEN DESIGN, ASSEMBLY, AND CURE

Ply Sequence

The lay up sequence for the baseline specimen of this study was sized to be compatible with the designs of the various concepts in the early phases of the Reference 3 program. These specimens in the referenced program were configured with ten plies in the stem and forty plies in the base; with the top five plies of the base forming the respective halves of the stem.

Numerous ply arrangements were proposed in the Reference 3 effort, thus the selection of the baseline specimen for this study was a compromise in properties with a tendency to increase the stiffness in the 90° direction, and reduce the strength in the 0° direction (Figure 10). The baseline specimen was sized to approximately match the thickness of the Reference 3 specimens. To achieve these various requirements the following rationale was applied:

A. One woven ply approximated two unidirectional plies in thickness,

B. One woven ply oriented at 45°, denoted W($\pm$45), was typically substituted for a $\pm$45° set of unidirectional material,

C. One woven ply oriented orthogonal to the spar direction, W(0/90), was substituted for two 0° unidirectional plies in the

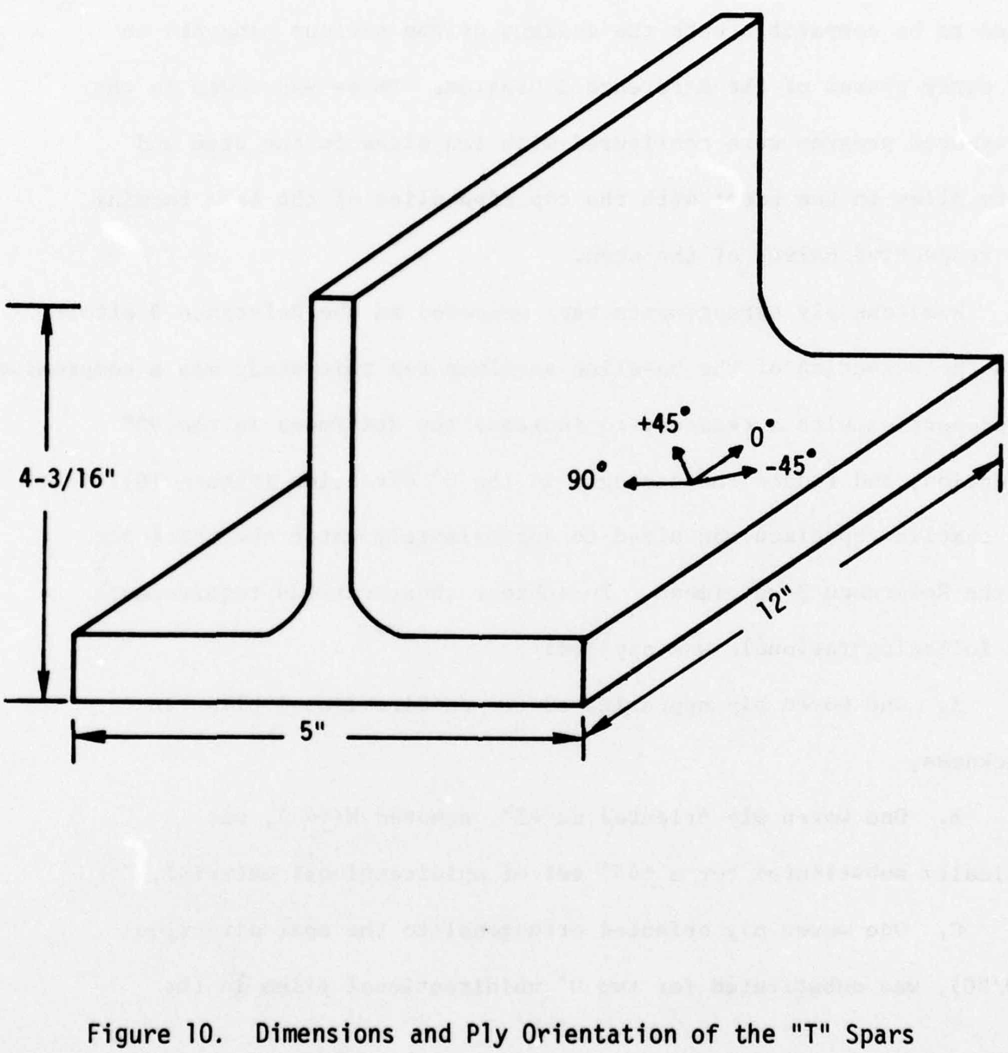


Figure 10. Dimensions and Ply Orientation of the "T" Spars

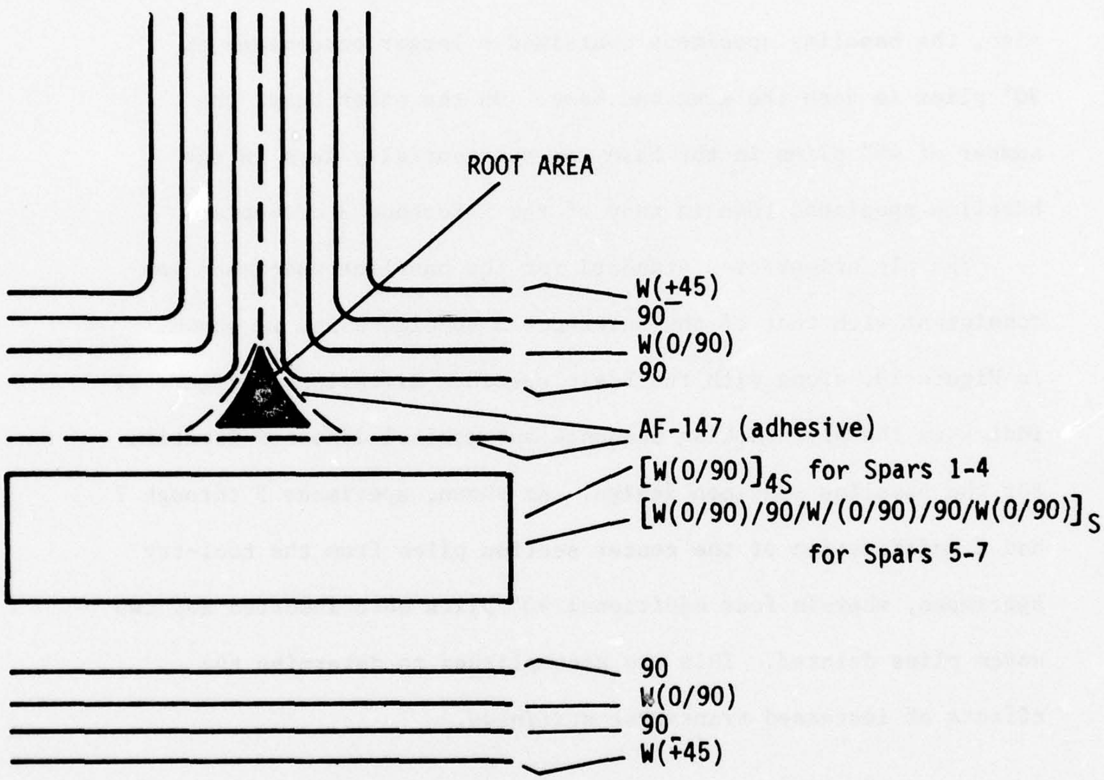


Figure 11. Lay-up Sequence of the "T" Spars

center section of the base (middle thirty of forty plies for the Reference 3 specimens). This sizing led to a baseline specimen design that was slightly thicker than the Reference 3 specimens. Also, the baseline specimens contained a larger percentage of 90° plies in both the stem and base. On the other hand, the number of 45° plies in the base was substantially less in the baseline specimens than in many of the Reference 3 concepts.

The ply orientation standard for the baseline specimens was consistent with that of the Reference 3 specimens and is shown in Figure 10, along with the basic specimen dimensions. Figure 11 indicates the ply stacking sequence and nominal adhesive location for the baseline specimen design. As shown, specimens 5 through 7 had a modification of the center section plies from the tool-try specimens, wherein four additional 90° plies were inserted and two woven plies deleted. This was accomplished to determine the effects of increased transverse stiffness.

Materials

Material selection for the program was based on a compatible set of woven and unidirectional graphite/epoxy preimpregnated (prepreg) material that was selected in a then-recently terminated research program at the Columbus Aircraft Division of Rockwell International (Reference 4). This baseline material was on hand

for immediate use on this program. Although it was somewhat overaged, the flow and tack were satisfactory. Thus, this material was judged appropriate for verifying the tool concept and developing the root concept. For failure modes that are resin dependent, this material was considered as satisfactory for indicating the types and location of failure, but not the load magnitudes. Thus, a new batch of material, formulated with Hercules 3501 resin, was procured and a set of tests were conducted to compare failure magnitudes and modes with the baseline material of this study. The following baseline materials were used:

1. Woven Graphite/Epoxy

Fiberite - HMF 330C/34 (42 inch width prepreg)

(a) Fabric Parameters (nominal)

Volume Ratio (warp/fill)	0.93/1
Weave	8 Harness Satin
Weight (oz/yd^2)	12.0

(b) Prepreg Parameters

Resin Content (wt.%)	42.7
Volatile Content (wt.%)	0.98
Flow (%)	16-24

(c) Composite Properties (nominal minimum values)

Warp Tensile Strength (psi)	75,000
Warp Tensile Modulus (psi)	9.3×10^6
Warp Compressive Strength (psi)	72,000

Warp Compressive Modulus (psi)	8.75×10^6
Short Beam Shear (warp, psi)	7,000
Specific Gravity (gm/cm^3)	1.58

(d) Composite Property (measured from batch used)

Ply Thickness (cured, in)	.014

2. Unidirectional Graphite/Epoxy

Fiberite - hy - E 1050C (2 inch width prepreg)

(a) Prepreg Parameters (nominal)

Resin Content (wt. %)	40 ± 3
Volatile Content (wt. %)	2

(b) Composite Properties (nominal minimum values)

0° Tensile Strength (psi)	235,000
0° Tensile Modulus (psi)	23.5×10^6
Short Beam Shear Strength (psi)	14,000
Specific Gravity (gm/cm^3)	$1.55 \pm .03$
Fiber Volume (%)	65

3. Film Adhesive

3M Bonding Film AF-147

(a) Manufacturer's Description

Color	Gray - Tan
Base	Modified Epoxy
Form	Flexible Scrim Supported
Weight (lbs/ft^2)	0.080
Volatile Loss on Cure (wt.%)	Less than 2.0% (350°F, 1 hr.)

The woven prepreg and unidirectional materials used for comparative purposes were as follows:

1. Woven Graphite/Epoxy (42 inch width prepreg)

   Special order T300/3501-6. Nominal mechanical properties have not been determined. T300 fiber was woven instead of Hercules AS fiber after problems were encountered by the weaver (Fiberite) with the AS fibers

   (a) Prepreg Parameters

Resin Content (wt. %)	41
Volatile Content (wt. %)	2.2
Flow (%)	25

2. Unidirectional Graphite/Epoxy

   Hercules AS/3501-5A (12 inch width prepreg)

   (a) Prepreg Parameters (nominal)

Resin Content (wt. %)	42 $\pm$ 3
Volatile Content (wt. %)	2 (maximum)

   (b) Composite Properties (nominal minimum values)

0° Tensile Strength (psi)	230,000
0° Tensile Modulus (psi)	$20 \cdot 10^6$
Short Beam Shear Strength (psi)	17,500
Specific Gravity (gm/cm^3)	1.61
Fiber Volume (%)	64
Ply Thickness (cured, in)	0.0052$\pm$0.0003

Assembly

The lay-up of a "T" spar was done in five steps, as outlined in Figures 12, 13, 14, and 15. The details of the assembly are described below:

1. The right and left handed "L"s that go together to form the upper part of the "T" spar were cut and laid up [W($\pm$45)/ 90/ W(90/0)/ 90] on their respective mold faces.

2. The film adhesive was added as shown in Figures 13A and 13B.

3. The right and left handed "L" sections were joined and they formed the "T" (Figure 14A).

4. The filler was inserted into the root area and a small section of the film adhesive covered it (Figure 14A and 14B).

5. The lower base-section was laid-up [W$(90/0)_{4S}$/ 90/ W(0/90)/ 90/ W($\pm$45)] and mated with the top of the spar (Figures 15A and 15B). The uncured "T" spar was now ready for insertion into the mold assembly. A cross-section of the assembled mold is shown in Figure 1.

All metal surfaces were sprayed with a teflon-spray mold release compound. To minimize difficulties with the resin migration into the bolt holes, a "moly-coat" coating was applied to the bolts and threads.

Bleeder material used was a polyester mat, Mochburg Cloth No. CW1850, manufactured by the West Coast Paper Company, Seattle, WA.

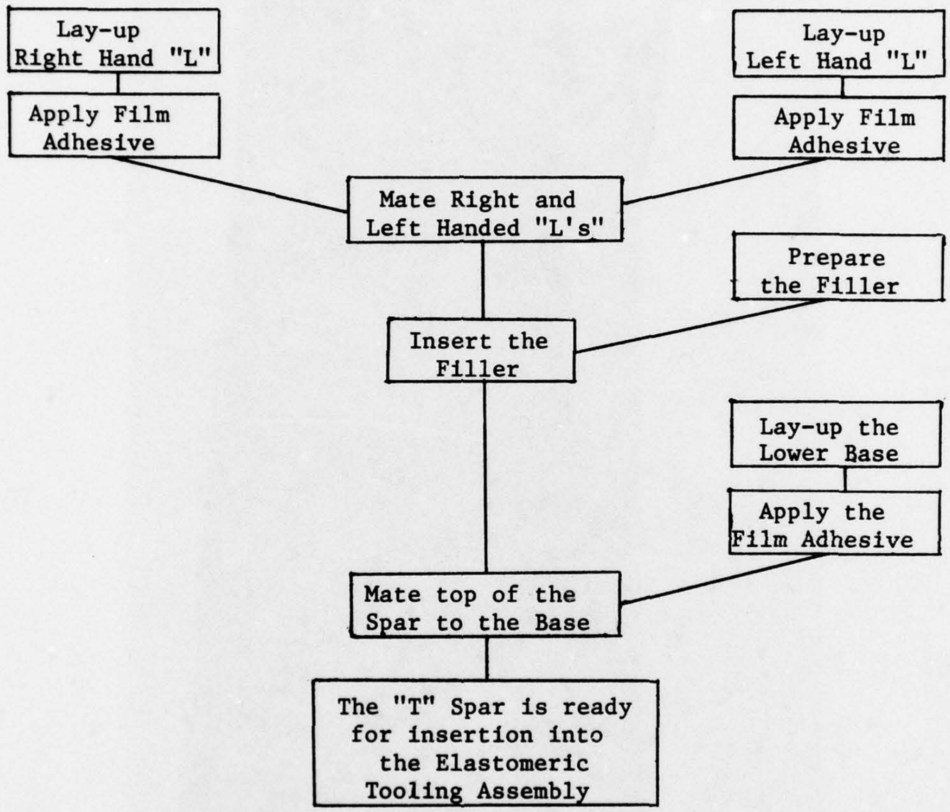


Figure 12. Fabrication Sequence of the "T" Spars

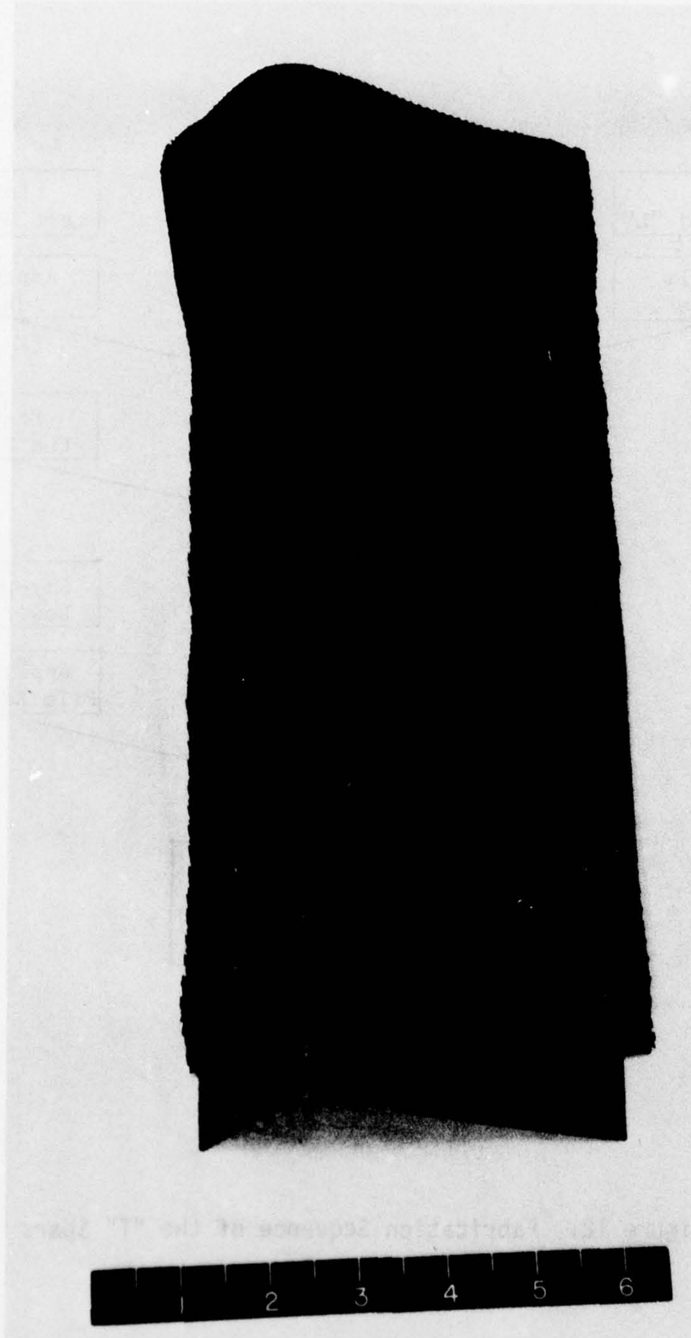


Figure 13A. Forming the Right-Hand Half of the Stem

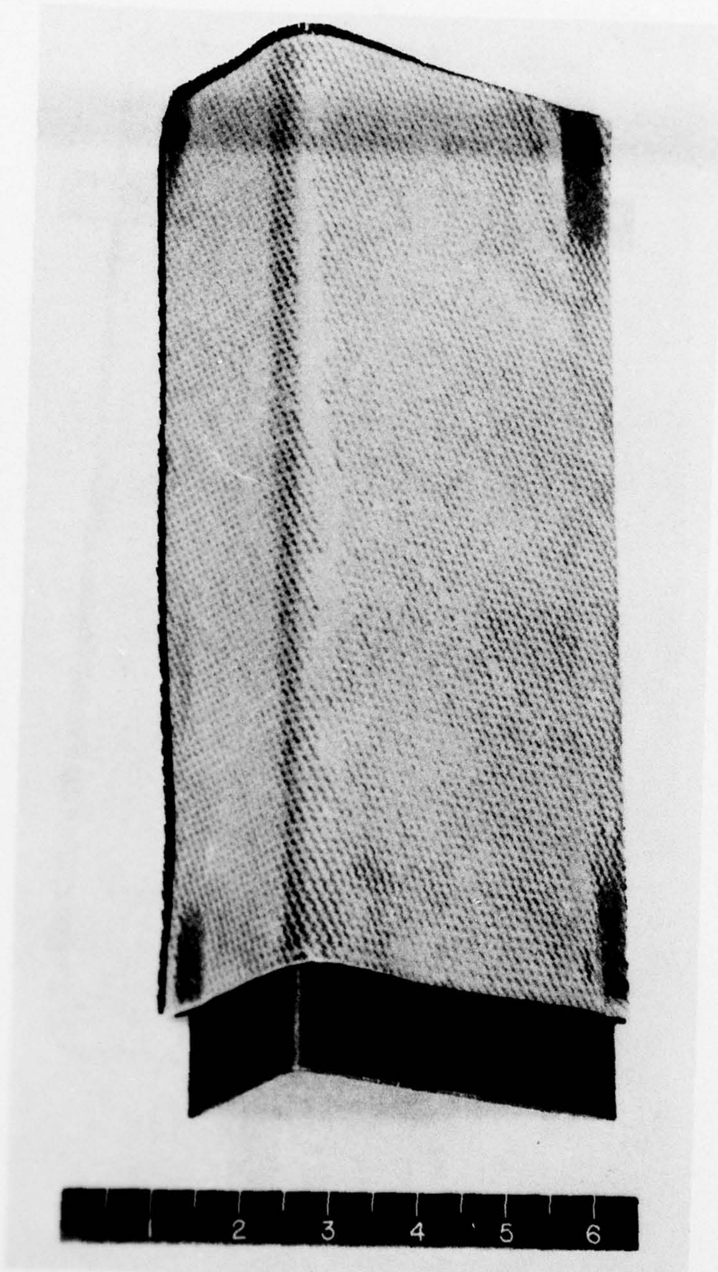


Figure 13B. Addition of the Film Adhesive to the Right-Hand Half of the Stem

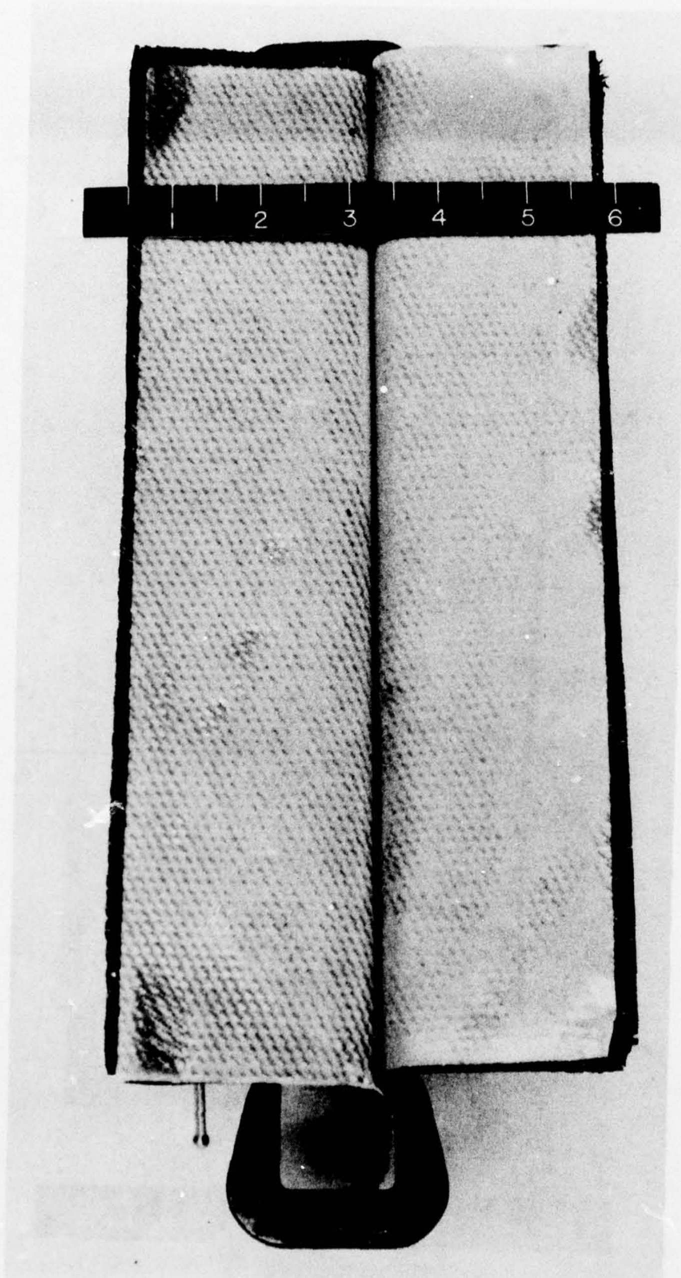


Figure 14A. Mate the Right and Left Hand Havles to Form the Stem

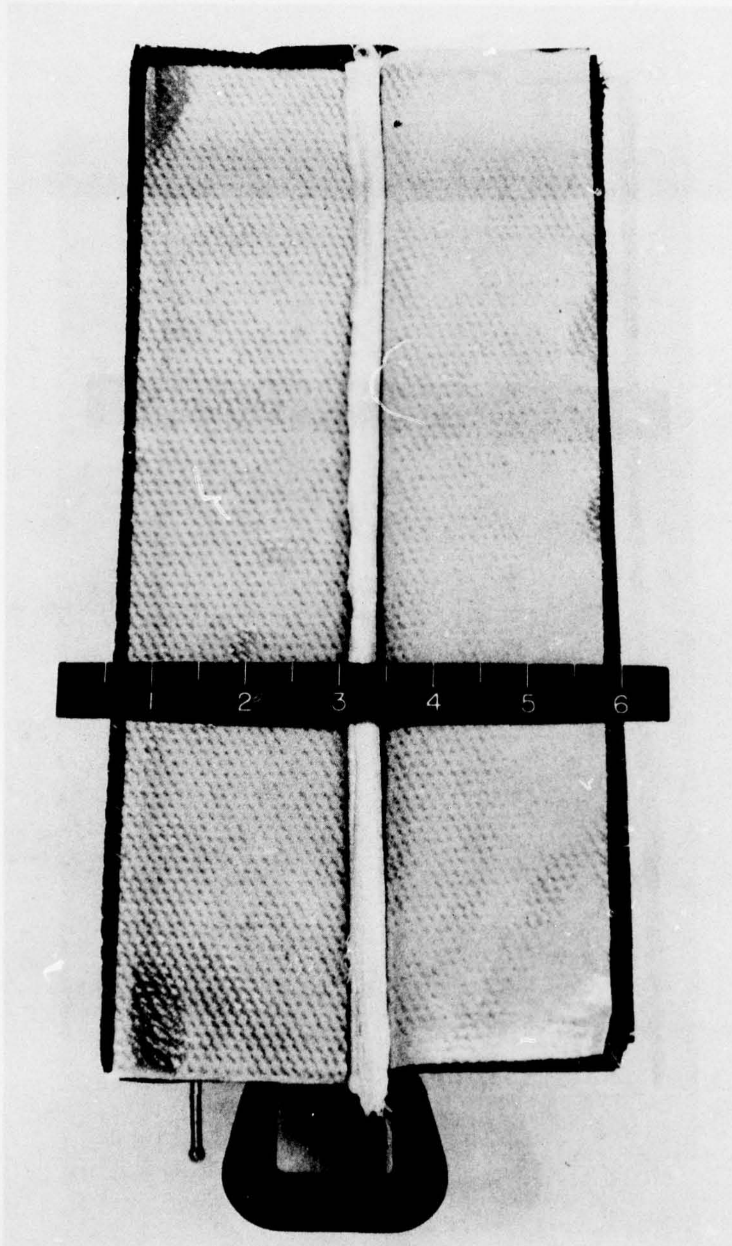


Figure 14B. Addition of the Filler into the Root Area of the Stem

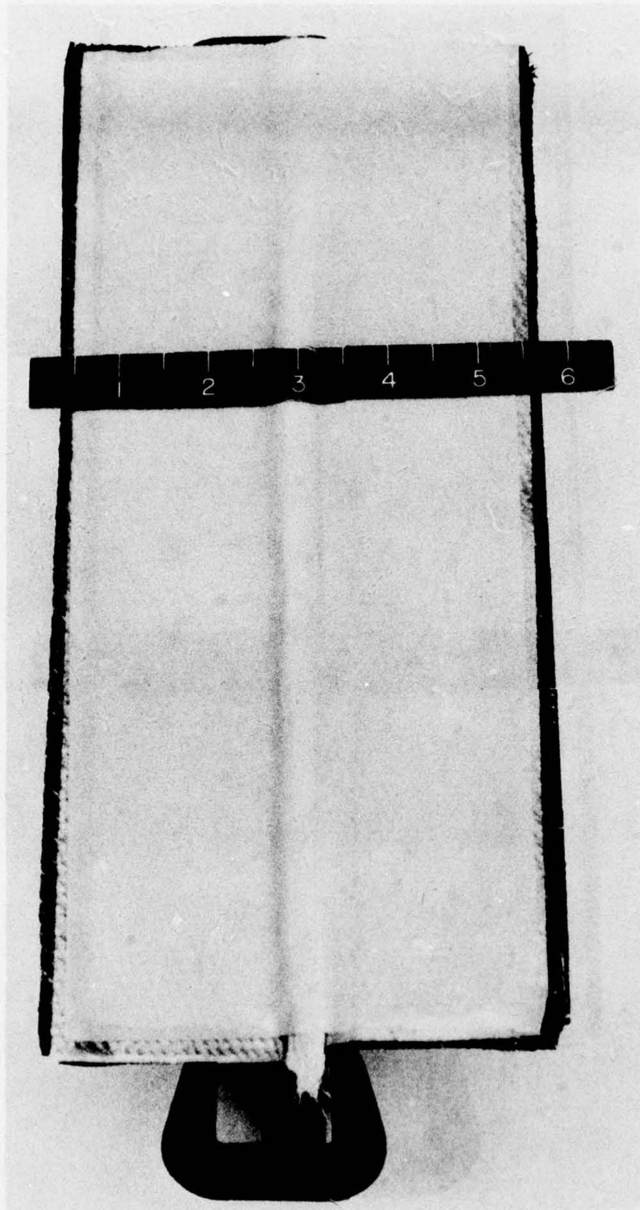


Figure 15A. Addition of the Film Adhesive to the Base

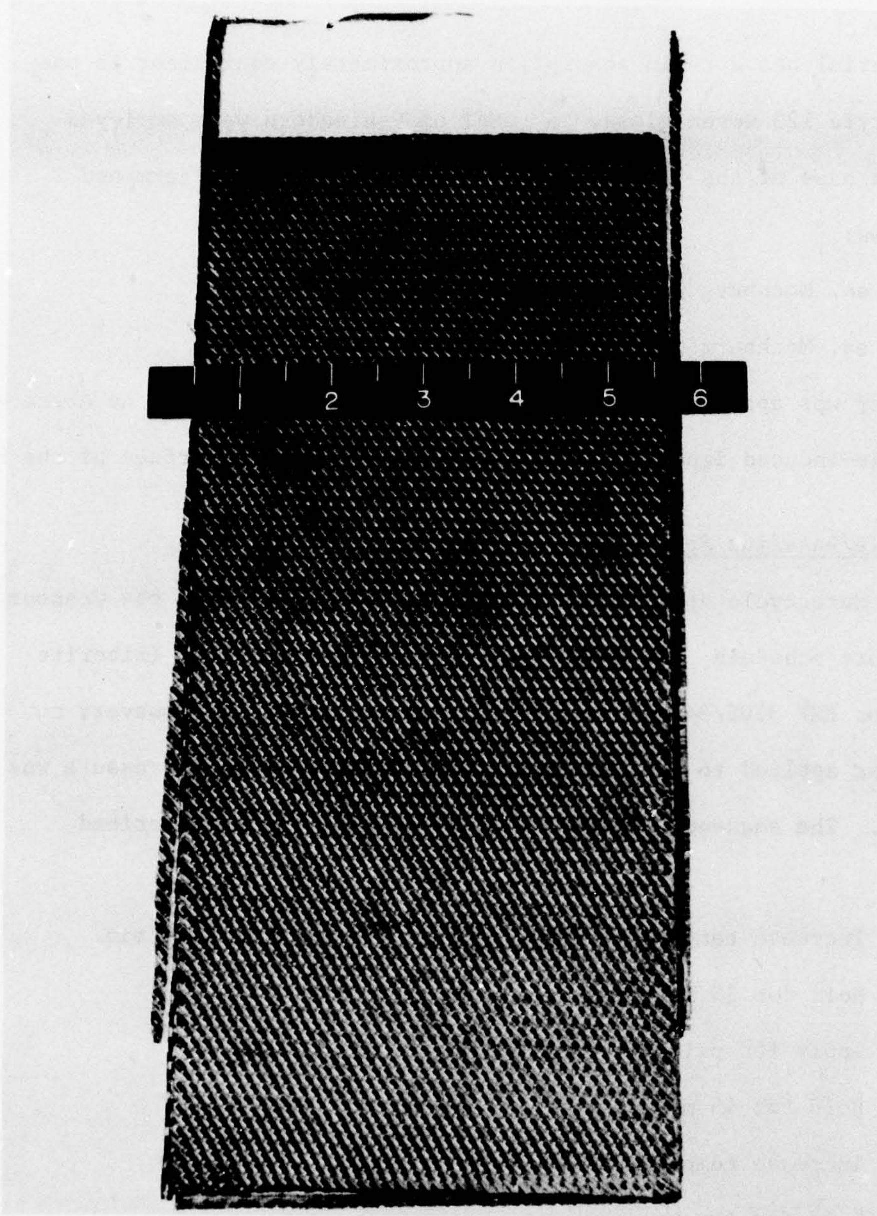


Figure 15B. Mate the Stem with the Base

This material has a resin absorption approximately equivalent to one ply of Style 120 woven glass. A total of 9 bleeders were employed below the base of the laminated spar. This number was determined as follows:

1 ea. Mochburg per 1 1/2 plies woven prepreg

1 ea. Mochburg per 3 plies unidirectional prepreg

No bleeder was applied adjacent to the stem plies to assure the absence of wrinkle-induced imperfections in the stem and upper surface of the base.

Cure Cycle/Baseline Spars

The cure cycle applied to all baseline spars followed the pressure/temperature schedule recommended by the material supplier (Fiberite Corp.) for HMF 330C/34 and hy-E 1050C resin composites. However, no vacuum was applied to the part and a compensatory initial pressure was not used. The sequence of events for the cure cycle is described below:

1. Increase temperature from ambient to 250°F at 5° F/min.
2. Hold for 15 minutes.
3. Apply 100 psi.
4. Hold for 45 minutes.
5. Increase temperature to 350°F at 5°/min.
6. Hold for two hours.
7. Cool under pressure to below 140°F.

To insure uniformity of heat-up rates, 12 thermocouples were used to monitor the temperature of the part. Thermocouple locations are described in Figure 16 and Table 1. To minimize uneven heating due to air currents in the forced air oven (Figure 17), the metal box was placed inside a cylinder of asbestos sheeting after Spar-Two had been fabricated. The 100 psi curing pressure was obtained from a regulated air compressor.

Cure Cycle/Hercules 3501

The cure cycle for the comparative specimens followed the nominal industry specifications recommended by the supplier, excepting the absence of vacuum. This cycle was as follows:

1. Apply 15 ± 5 psi bladder pressure.
2. Increase temperature from ambient to 225 ± 10°F at 5°F/min.
3. Increase pressure to 100 psi.
4. Hold one hour.
5. Increase temperature from 225°F to 350°F at 5°F/min.
6. Hold for one hour.
7. Cool under pressure to below 140°F.

Machining

After cure each spar was ultrasonically scanned to detect voids or delaminations using through-transmission C-Scan equipment. The spars were subsequently sectioned into 1 in. wide "T" specimens using a water cooled diamond cut-off wheel. An initial 3/4 in. trim was accomplished

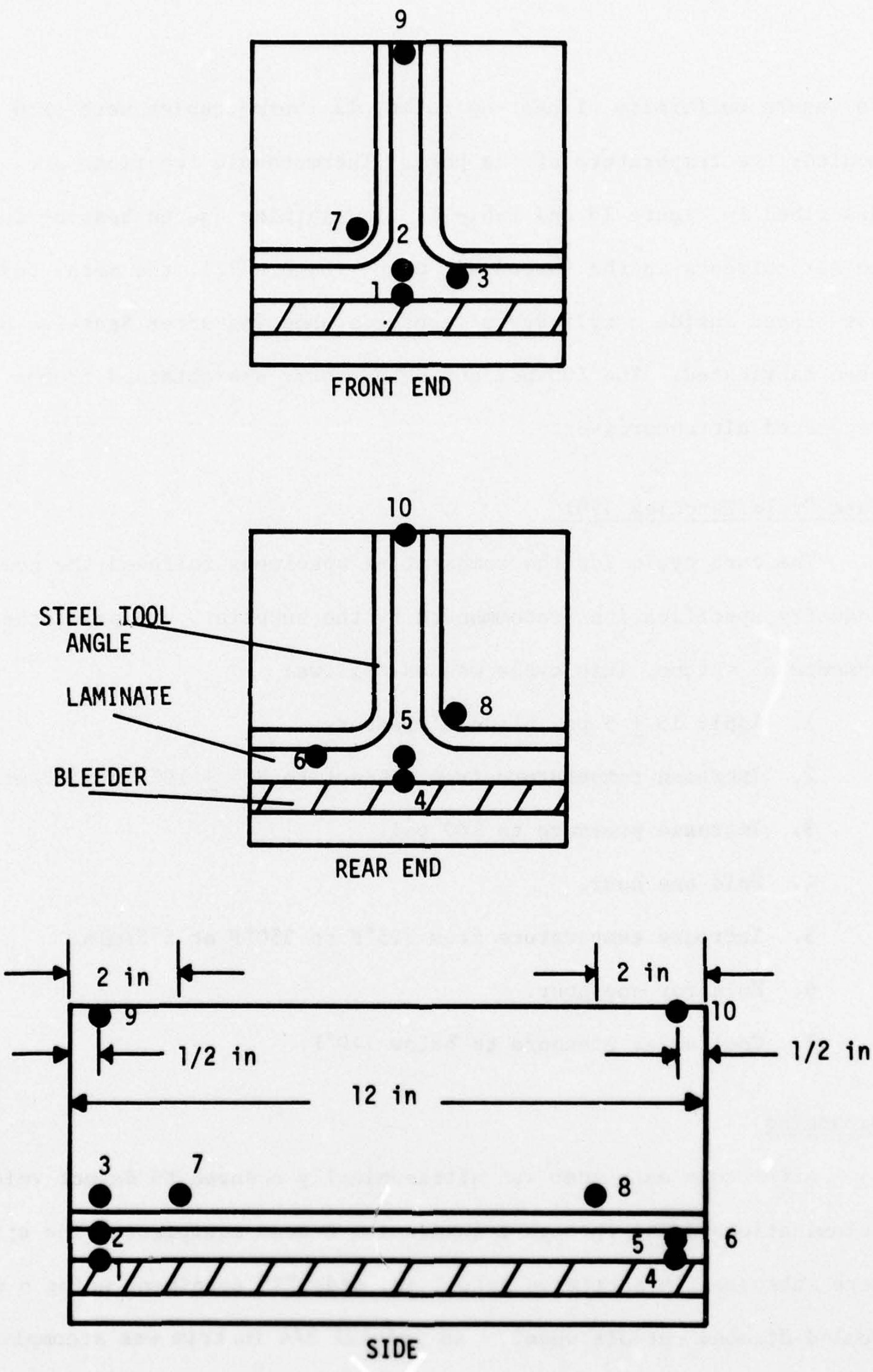


Figure 16. Location of the Thermocouples

TABLE 1.

LOCATION OF THERMOCOUPLES

T/C#	Location
1	bottom of base, 1/2 in. in from the front edge
2	1/2 in. inside the root section from the front edge
3	top right hand side of the base, 1/2 in. in from the front edge
4	bottom of base, 1/2 in. in from the rear edge
5	1/2 in. inside the root section from the rear edge
6	top left hand side of the base, 1/2 in. in from the rear edge
7	between the metal caul and the rubber tool, 2 in. in from the front left hand side
8	between the metal caul and the rubber tool, 2 in. in from the right hand side
9	on top of the stem, 1/2 in. in from the front side
10	on top of the stem, 1/2 in. in from the rear side
11	outside of the metal tooling box in the rear of the box
12	outside of the metal tooling bos in the front of the box

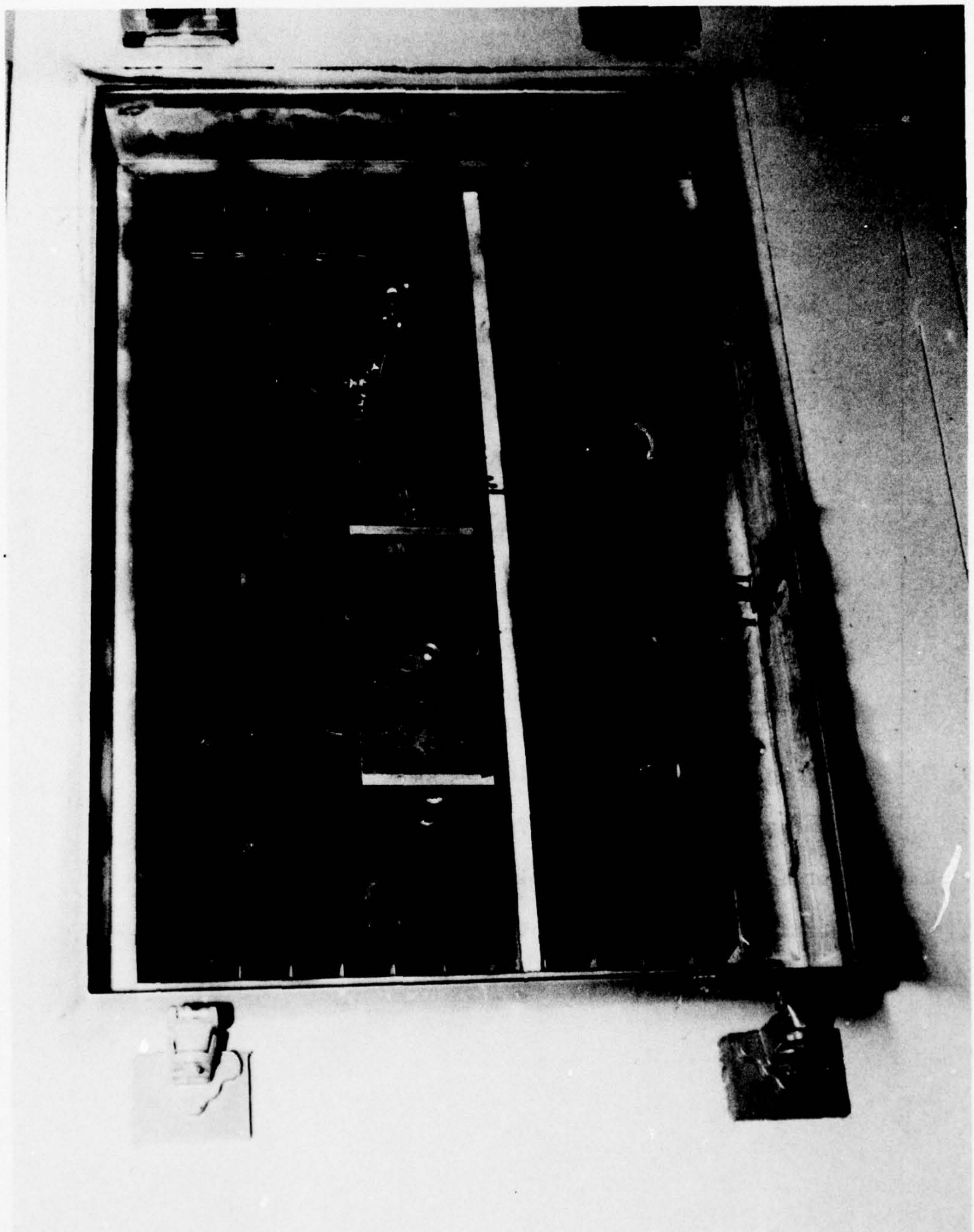


Figure 17. Elastomeric Tool in the Forced Air Oven

prior to cutting the test coupons. Specimens were numbered in consecutive, increasing order starting with number 1.

IV. TEST TECHNIQUE

The test technique used in this program and the Reference 3 effort was developed concurrently. Each "T" specimen was subjected to three point loading; i.e., a tensile pull along the stem, with the base restrained at each end. This test condition, with the proper span between the load points on the base, allowed the stem/base juncture (root area) to deflect in a manner simulating the spar-to-cover interface in a pressurized (integral fuel tank) wing (Reference 5). Two methods of end restraint were originally considered in Reference 3. In one the base was clamped, restricting end rotation. The other method employed pin-supports on the base and was predominantly used in Reference 3 with a span (between pins) on 2.67 in.

As developed for the Reference 3 program the load conditions governing this joint included a stem design load of 360 lbs/in. of width (0° direction) and a corresponding bending moment of 240 in.-lbs/in. at the stem base region. To achieve this condition, a clamped test fixture would require a span (distance along the base between clamps) of 5.33 in. (Reference 5). If simple supports were used, the span should be the 2.67 in. used in Reference 3. At the start of this program, available data for similar spar concepts (Reference 6) had been developed for a 2 in. span/clamped condition. Thus, data developed in this program were for a 2.67 in. span/simple support and a 2 in. span/clamped condition.

Figure 18 shows the test fixture with a "T" specimen in the clamped mode. Figure 19 indicates the simple-support load condition. The test fixture was fitted to a 20,000 lbs Instron Universal Test Machine. A gage length of 2 in. was established between the Instron wedge grip ends and the nearest horizontal surface of the spar (first ply of the base). The cross head speed was 0.005 ipm for tests on Spars 5-7, but was increased to 0.01 ipm for tests on Spars 1-3 (tested at the program completion). Fiberglass reinforced plastic tabs normally used at the gripping ends of composite tensile coupons were not necessary based upon the mode and restricted location of failure at the stem-to-base juncture. That is, grip induced failures were not probable since failure loads in the root area were well below the strength of the stem laminate.

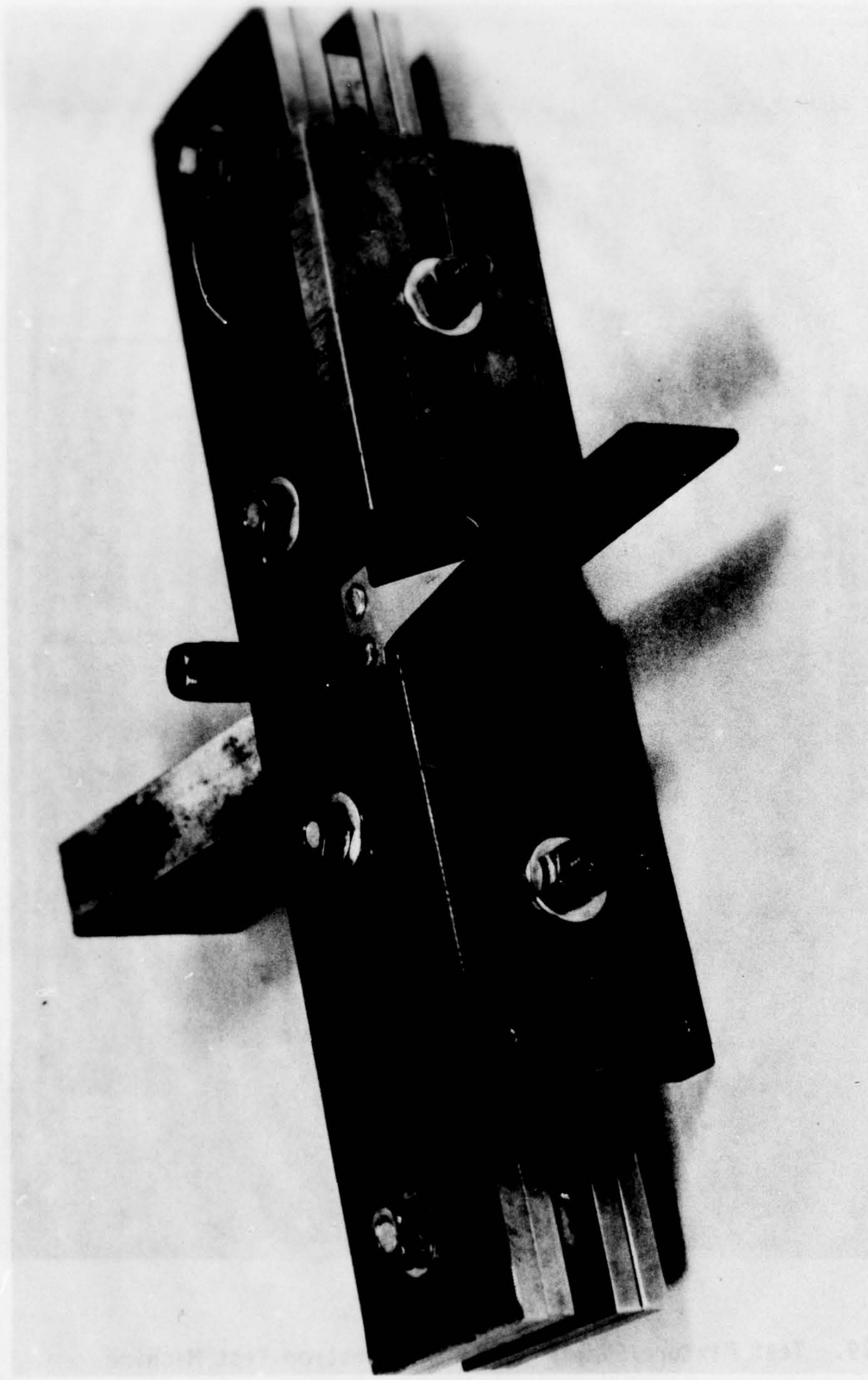


Figure 18. Flat-wise Tension Fixture/Clamped Edges

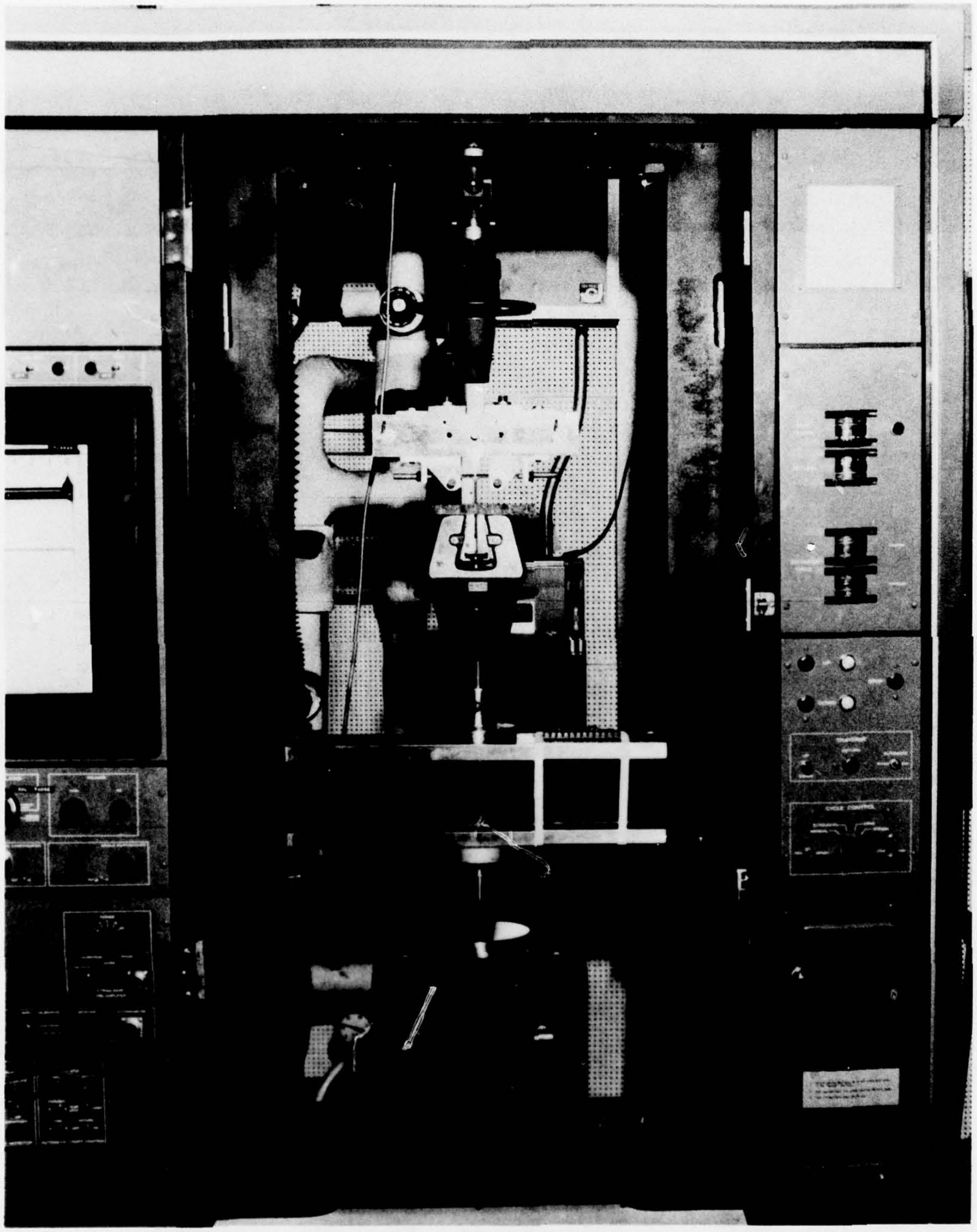


Figure 19. Test Fixture/Simple Support in Instron Test Machine

V. EVALUATION OF THE "T" SPARS

A total of seven "T" spars were fabricated by the controlled pressure elastomeric tooling process. The initial four were considered tool-try articles, and were primarily fabricated to determine dimensional reproducibility, the reliability of the bladders, and thermal profiles. The latter spars constituted prototype models used to evaluate root area concepts, to obtain a quantitative determination of the flatwise tensile strength, and to determine the modes of failure in a flatwise tension.

Spar-One

This spar was laid up as described in Figure 12 (the configuration without 90° unidirectional material in the central core), with the exceptions that neither adhesive nor root filler were used. The spar appeared to be sound, both optically and with a coin tap. The stem and the base were well compacted indicating that adequate pressure was applied during the curing process. Thickness measurements, shown in Table 2, indicate that the tool compacted both sides of the base evenly, and ultrasonic C-scans indicated the absence of large voids in either the base or the stem. A large dimple, approximately 1/16 in. deep, was noticed on the underside of the base directly beneath the root area and running the entire length of the spar. However, this was expected since no filler material was used in the root area of the spar.

TABLE 2.

THICKNESS OF TOOL-TRY SPARS

Spar No	Measured (in.)			Estimated (in.)	
		Base			
	Stem	Left	Right	Stem	Base
1	0.077	0.182	0.183	0.077	0.189
2	0.080	0.192	0.191	0.077	0.189
3	0.085	0.197	0.198	0.087	0.194

NOTES: (a) Estimated thickness based on a ply thickness of 0.014 in. for a woven laminate of HMF 330C/34, a ply thickness of 0.0052 in. for a unidirectional laminate of hy-E-1050C, and an adhesive thickness of 0.005 in.

(b) Measured thickness are an average of 3 points taken along lines one inch in from the stem top or base edges.

One-inch-wide specimens cut from Spar-One were tested in both the clamped and simply supported modes. Data are shown in Table 3 and will be discussed later in this report. The failure mode for these specimens was a vertical split in the stem just above the root, followed by an interply peel-type failure in the base plies that washed, or dimpled, into the root void.

A temperature differential of 20°F was observed across the tool during the ambient to 250°F heat-up section of the cure cycle. Although, the internal temperature increase of 2°F/min was below the normal 4-6°F/min initially desired, the oven heat-up rate of 10°F/min (circulating air) was judged to be too high. Thus, the oven heat-up rate was reduced for the remainder of the program.

Spar-Two

This spar was laid up as described in Figure 12 with the exception that no adhesive was used in the stem or the base. A filler was used in the root area. It was formed by rolling a 2 in. wide by 12 in. long piece of unidirectipnal prepreg into a cylinder approximately 1/4 in. in diameter by 12 in. in length, such that fibers ran into the root area of the spar as described by Figure 14B.

After cure, Spar-Two appeared to be sound. As with Spar-One, both the base and the stem were close to their expected thicknesses (Table 2), indicating an adequate cure pressure. Ultrasonic C-scans also indicated the absence of large voids in the stem and the base. A small dimple, 1/32 in. in depth, was observed under the root area similar to the one observed in Spar-One. This implied that an

TABLE 3.

DIMENSIONAL THICKNESS OF SPAR-FIVE

	Base (inches)		Stem (inches)
	Right Side	Left Side	
1	0.1929	0.1892	0.0787
2	0.1900	0.1891	0.0797
3	0.1925	0.1914	0.0815
4	0.1954	0.1938	0.0823
5	0.1946	0.1942	0.0829
6	0.1948	0.1939	0.0833
7	0.1939	0.1909	0.0815
8	0.1911	0.1915	0.0807
9	0.1946	0.1897	0.0807
10	0.1949	0.1934	0.0798
11	0.1942	0.1963	0.0795
Average	0.1935	0.1921	0.0810
Std. Dev. calc. by the N-1 method	0.0016	0.0024	0.0015

Note: All measurements were taken on 1-inch centers along the length of the spar, 1 inch in from each trimmed edge.

insufficient amount of filler was placed in the root area, or that resin was flowing up the stem. A temperature differential of 20°F was observed across the tool during the heat-up from ambient to 250°F in the cure cycle. For all future cure cycles, an asbestos cylinder was placed around the metal box to minimize unequal heating due to air currents in the forced air oven and a 2-3°F/minute oven heat-up rate was used. This led to comparable internal temperature increases in the laminate.

Spar-Three

Spar-Three had the same lay-up as Spar-Two. However, AF-147 film adhesive was used in the stem and base, as illustrated by Figure 12. A 4 in. wide x 12 in. long piece of unidirectional prepreg was formed as in Spar-Two and inserted into the root area.

During the cure heat-up from ambient to 250°F temperature hold, a maximum deviation of 12°F occurred across the tool. Ultrasonic C-scan of the cured spar indicated that there were no large voids in either the base or the stem of the spar. Thus, the stem and the base were well compacted indicating an adequate cure pressure. An extremely small dimple, less than 1/64 in. deep, was observed under the root area.

Spar-Four

This spar had the same lay-up as Spar-Three. However, "AS" graphite fibers (manufactured by the Hercules Corporation) and a 4 in. wide x 12 in. long piece of unidirectional prepreg were combined and rolled into a cylinder. The graphite fibers were oriented parallel to the length of the cylinder. This cylinder was inserted into the root area of the spar.

At the 100 psi pressure application point in the cure cycle, one of the elastomeric bladders developed an air leak and the cure cycle was terminated. Examination of the elastomeric bladder indicated that a thermocouple wire was apparently inserted through the bladder wall when the metal fixture was being prepared for the curing process. The hole in the elastomeric bladder was repaired using Dow Corning Silastic® 732 RTV adhesive/sealant. This spar was considered a reject and no further tests or analyses were accomplished.

Strengths of Spars-One, Two, and Three

The inplane tensile strengths of the tool-try spars were determined at a load rate of 0.01 ipm. As shown in Table 4, the insertion of an adhesive layer at high interply tensile stressed areas tended to increase the joint strength. The greater strength of the Spar-One specimens over the Spar-Two specimens might be attributed to the crosswise or horizontal strengthening of the root area by

the base fibers that filled the root void (as contrasted with the transversely weak root of Spar-Two). However, definitive conclusions in this regard can not be made from these small data samples.

Spar-Five

In this spar, the ply configuration in the base was changed from the previous spars by adding four extra 90° plies and deleting two woven plies, as shown in Figure 12. The filler and adhesive used in this spar were the same as used in Spar-Four.

The maximum thermal differential across the part during the ambient to 250°F temperature hold in the cure cycle was 10°F, and the laminate temperature increased at 2°F/min. The part appeared to be sound. The base and the stem were uniform in thickness from one end to the other as indicated in Table 3. Both the base and the stem were close to their expected thickness, indicating adequate cure pressure. No dimple was observed. After trimming 0.5 in. from all edges of the spar, six one inch wide specimens were sliced from the spar and tested in flat-wise tension at a rate of 0.005 ipm. This rate was selected to aid in the visual observation of the failure mode. The failure loads of these specimens are given in Table 5 with the average strengths listed in Table 4.

TABLE 4.

FAILURE LOADS SUMMARY

Spar No	Average Failure Load (lb) Pinned Test	Average Failure Load (lb) Clamped Test	Clamped Failure Load / Pinned Failure Load
1	268	570	2.1
2	240	453	1.9
3	440	806	1.8
5	359	778	1.4
6A	593	1011	1.7
6B	530	796	1.5
7A	485	-	-
7B	712	-	-

Note: Spar No. 4 was not properly cured and was not tested.

TABLE 5.

FAILURE LOADS OF SPECIMENS FROM SPAR-FIVE

Specimen No	Failure Load (lb)	Load Condition
5-1**	670	Clamped/2 in. Span
5-2	865	Clamped/2 in. Span
5-3	800	Clamped/2 in. Span
5-4	345	Pinned/2.67 in. Span
5-5	363	Pinned/2.67 in. Span

NOTES: (a) The head speed was 0.005 ipm.

(b) **This specimen contained a partial thermocouple wire embedded in the root area which may have detracted from the strength. Also, many of the edge specimens from this program are weaker than those sectioned from the spar interior, even with a 1/2 inch edge trim.

(c) Specimens in this program are numbered in increasing order from 1, starting from the trimmed edge of the 12 in. as-cured spar.

The failure mechanism of the specimens described in Table 4 was complex, but all specimens basically failed by the same mechanism. Initially, a crack was observed to begin in the filled root area and grow vertically until the crack entered the adhesive layer above the filler or until the crack entered the adhesive layer under the filler, which runs parallel to the base. Below the root filler the crack ceased to grow vertically and it propagated horizontally in the woven ply immediately below the adhesive layer. Above the filler the crack jumped across the adhesive layer and ran vertically along the 90° unidirectional ply immediately above the adhesive layer. This process is illustrated in Figure 20. Photographs of two failed specimens from Spar-Five are shown in Figure 21.

Spar Six

Spar-Six was fabricated in one cure cycle as two half sections, 6 in. long and designated as Spar-6A and Spar 6-B.

a. Spar-6A

Spar 6-A was identical with Spar-Five with the exception of the root filler material. The filler material was formed by combining 1 sheet of AF-147 film adhesive, 2 sheets 104 woven glass scrim cloth, and 1 ply of graphite/epoxy unidirectional prepreg. These sheets were laid up, 2 in. wide by 12 in. long, rolled into a cylinder, and formed into the root area of the spar.

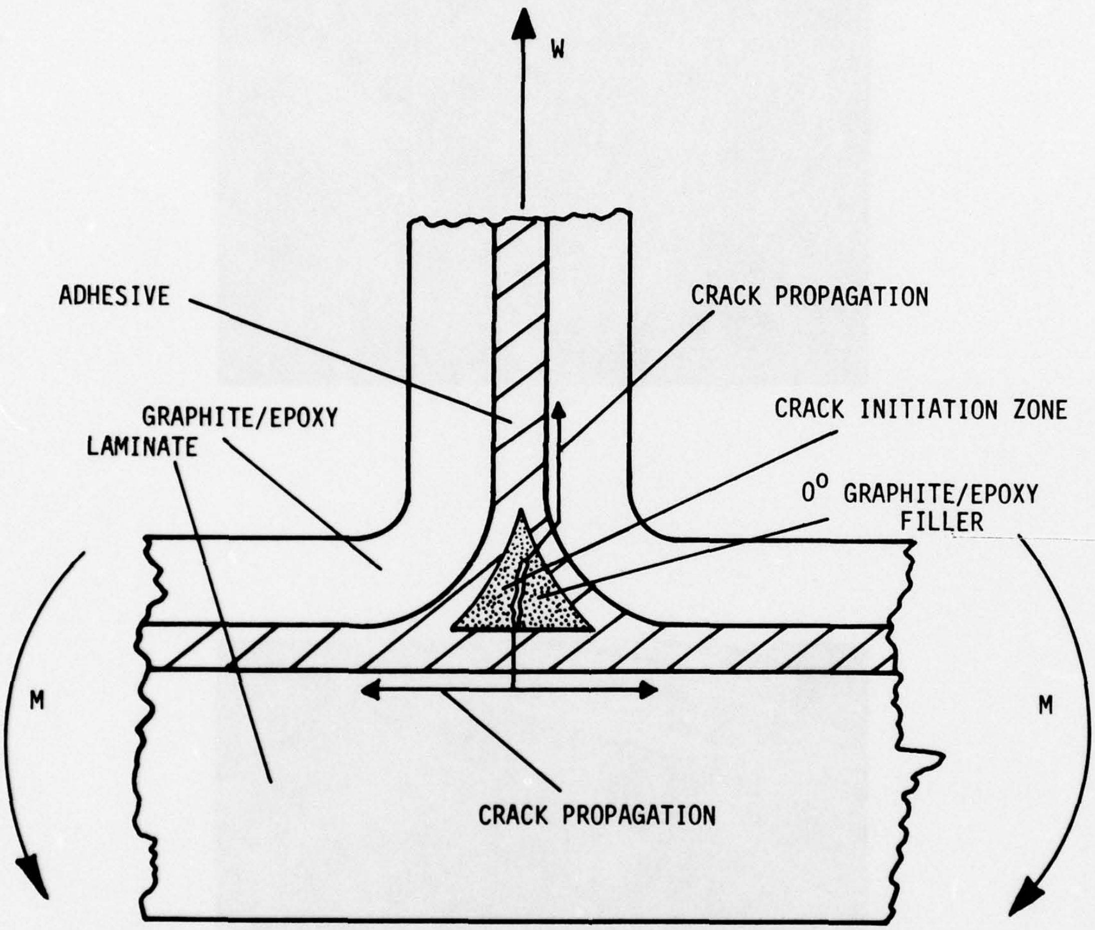


Figure 20. Failure Mechanism for Specimens from Spar - Five

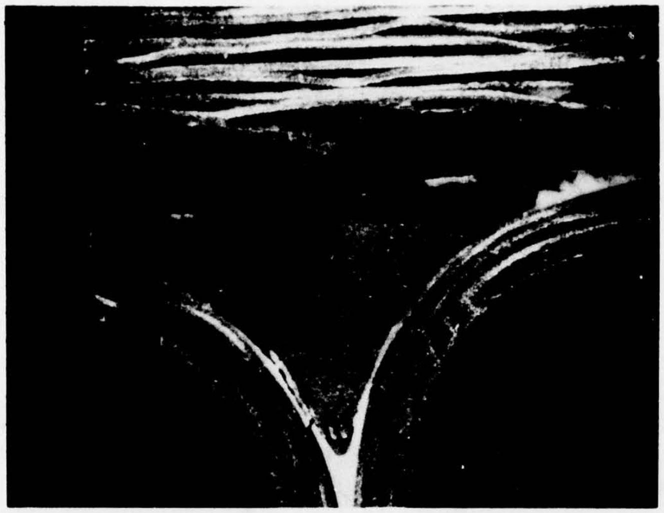


Figure 21. Typical Failed Specimen from Spar - Five

b. Spar-6B

Spar-6B was the same as 6A except that there was no adhesive in the stem.

The cured thickness of both the base and the stem of Spar-6A and 6B were close to their expected thicknesses. No dimples were observed under the root areas in either Spar-6A or Spar-6B. Ten specimens were machined from this spar. The test results are given in Table 6, where the application of adhesive between the stem halves appears to act as a softening strip to achieve a greater strength.

The failure modes for specimens from both Spar-6A and 6B were the same, with the exception of specimen 6B-2 where all failure occurred within the base plies. Crack initiation typically occurred in the woven graphite ply immediately under the adhesive layer between the base and the stem (Figure 22). The crack propagated horizontally along this ply. It also propagated vertically through the root filler material and grew along the 90° unidirectional ply above the adhesive layer on top of the root area. In the root filler, the cracks had a tendency to follow the 0° graphite especially where the spiral orientation was vertical, thus indicating the weakness of this root concept.

Spar-Seven

Spar-Seven was fabricated in two halves, designated Spar-7A and Spar-7B.

TABLE 6.

FAILURE LOADS OF SPECIMENS FROM SPAR-6A AND 6B

Specimen No	Failure Load (lb)	Load Condition
6A-1*	970	Clamped/2.5 in. Span
6A-2	1040	Clamped/2 in. Span
6A-3	982	Clamped/2 in. Span
6A-4	582	Pinned/2.67 in. Span
6A-5	604	Pinned/2.67 in. Span
6B-1	800	Clamped/2 in. Span
6B-2**	752	Clamped/2 in. Span
6B-3	835	Clamped/2 in. Span
6B-4	590	Pinned/2.67 in. Span
6B-5	470	Pinned/2.67 in. Span

NOTES: (a) *This specimen inadvertently had a span length of 2.5 in. and was not included in the Table 4 averages. (See Figure 18.)

(b) **This specimen failed by a different mechanism from all other specimens. Crack initiation started approximately in the 10th ply from the bottom of the base and propagated horizontally along a W(0/90) ply.

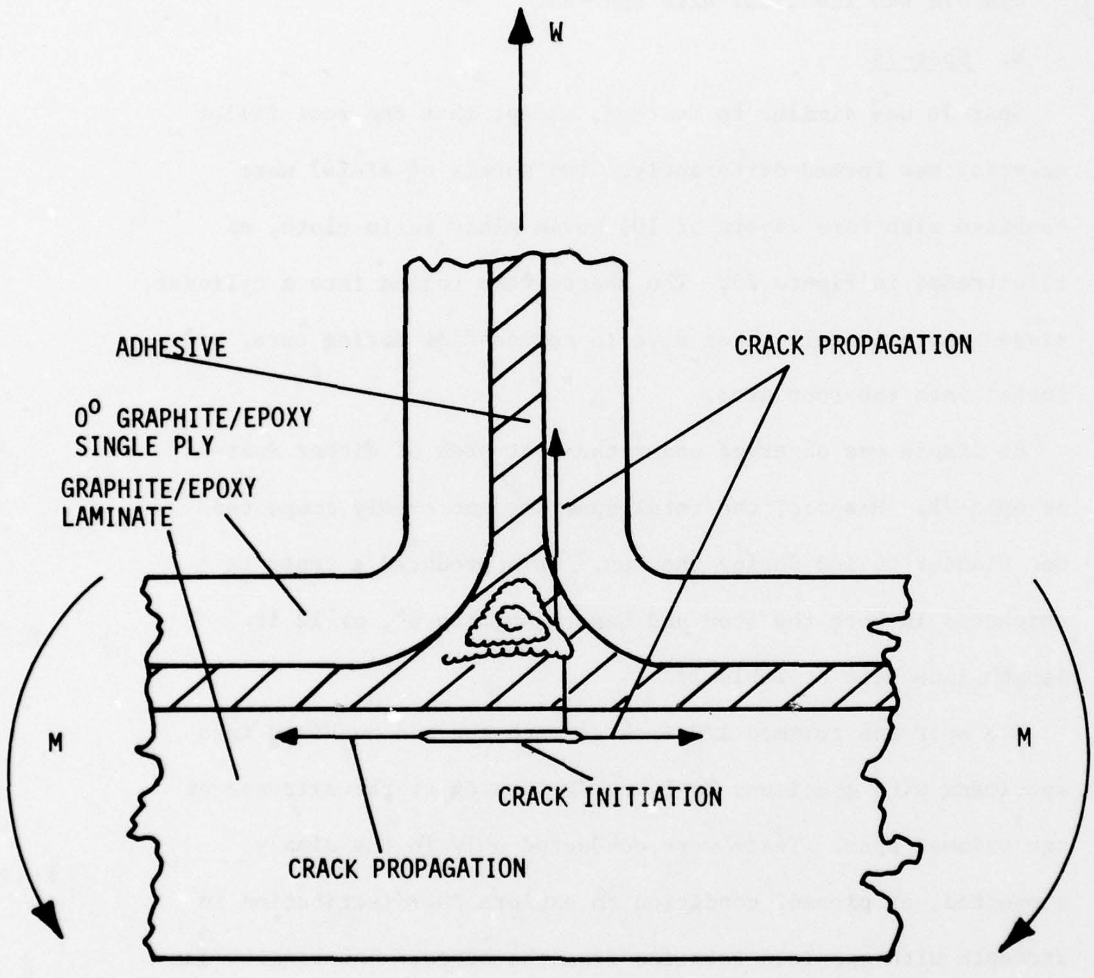


Figure 22. Failure Mechanism for Specimens from Spar-6B

a. <u>Spar-7A</u>

Spar-7A was identical with Spar-6A.

b. <u>Spar-7B</u>

Spar-7B was similar to Spar-6A, except that the root filler material was formed differently. Two sheets of AF-147 were combined with five layers of 104 woven glass scrim cloth, as illustrated in Figure 23. The sheets were rolled into a cylinder, stayed approximately three days to reduce flow during cure, and formed into the root area.

No dimple was observed under the root area of either Spar-7A or Spar-7B. However, the total spar was not evenly compacted. One bladder failed during the run. This produced a taper in thickness in both the stem and base along the 0°, or 12 in. length (see Note b, Table 7).

The spar was trimmed 1/2 inch at each end and machined into specimens with specimens 7A-1 and 7B-1 being at the extremes of the trimmed spar. Tests were conducted only in the simply supported, or pinned, condition to explore the distribution in strength with specimen location from the edges. The results are presented in Table 7, and the averages for each group of four are shown in Table 4. These data indicate the tendency for end specimens to be weaker than their centrally located counterparts (a characteristic later noted in Reference 3). The most prominent feature of this data

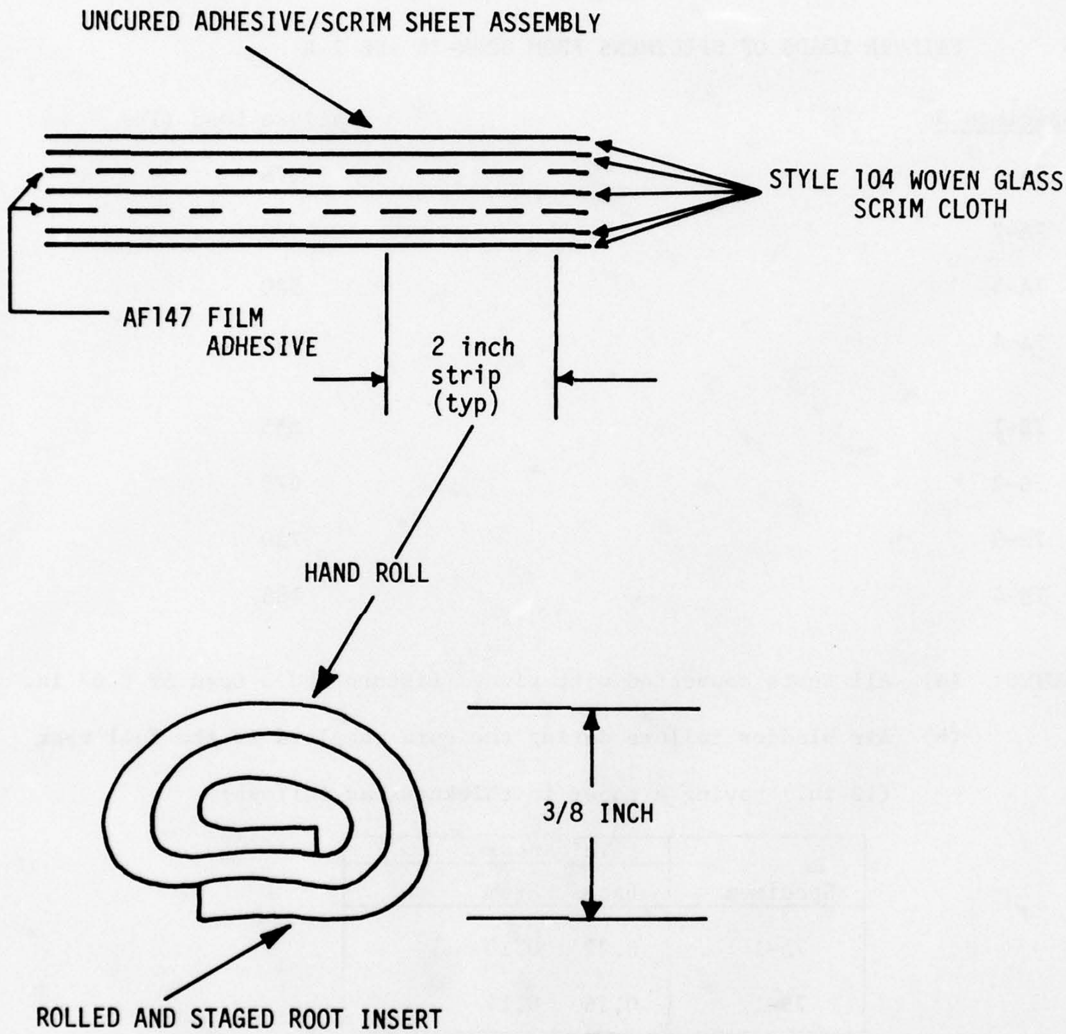


Figure 23. Preparation of the Root Filler Material Used in Spar 7B

TABLE 7.

FAILURE LOADS OF SPECIMENS FROM SPAR-7A AND 7-B

Specimen No	Failure Load (lb)
7A-1	376
7A-2	400
7A-3	520
7A-4	642
7B-1	655
7B-2	675
7B-3	730
7B-4	788

NOTES: (a) All tests conducted with pinned fixture and a span of 2.67 in.

(b) Air bladder failure during the cure resulted in the full spar (12 in.) having a taper in thickness as follows:

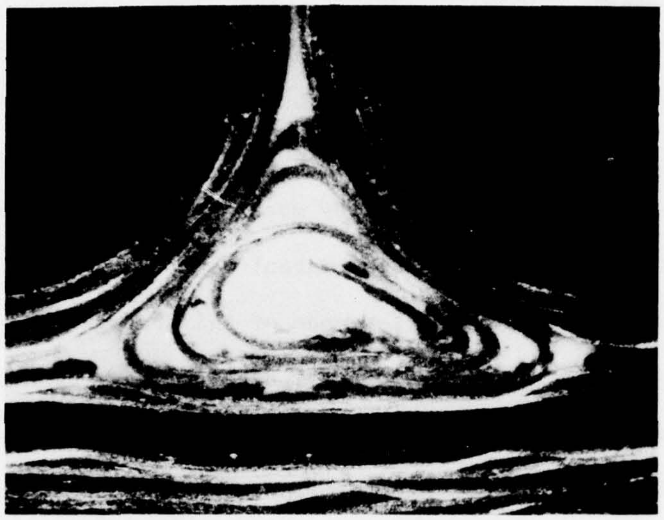
Specimen	Thickness	
	Base	Stem*
7A-1	0.22	0.10
7B-1	0.26	0.14

(c) *1/2 in. above root top.

is the greater strength of the specimens that were fabricated with the rolled scrim/adhesive root. However, an uncertainty clouds the reason for this strength, and the strength of Spar-7B relative to Spar-7A and Spar 6-A may more be due to its greater thickness and, thus, higher resin content than to the root configuration. Nevertheless, the mode of failure of Spars-6A and 7A, compared to Spar-7B, clearly indicates that the absence of transversely weak 0° plies in the root filler is desirable. Thus, Spar-7A failed in a manner similar to Spar-6 with cracks in the filler (Figure 24). Whereas, specimens from Spar-7B initially failed in the base with subsequent interlaminar fillet cracking (Figure 25). The fractures, however, skirted the high strength root filler.

Clamped vs Pinned Load Condition

The data in Table 4 was inserted to determine whether any relationship could be found between the clamped-to-pinned strength ratios and the average failure loads (W) in the stem. A relationship was not readily apparent. However, there was a tendency for the ratio to decrease as failure load increased. The two modes typifying initial failure in this program were vertical root cracks (stem direction) and interlaminar separation in the base plies. A complex stress profile in the failure zones between loads exists due to the bending moment (M) in the base and the tensile stem load. The elemental relation suggested in Reference 5 for comparing data developed using different



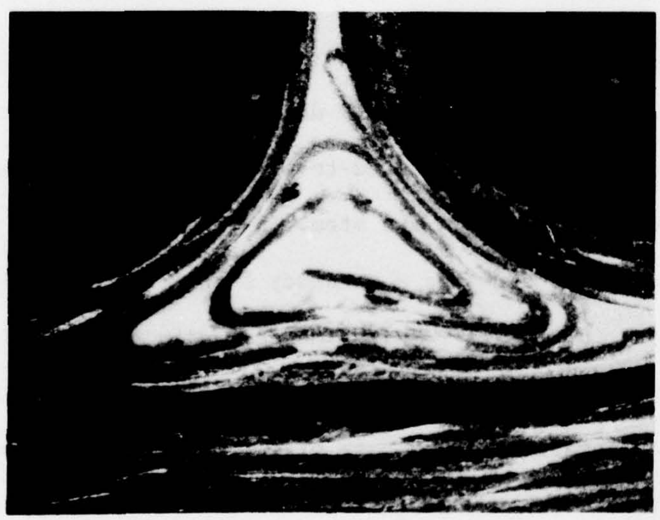


Figure 24. Typical Failed Specimens from Spar 7A.

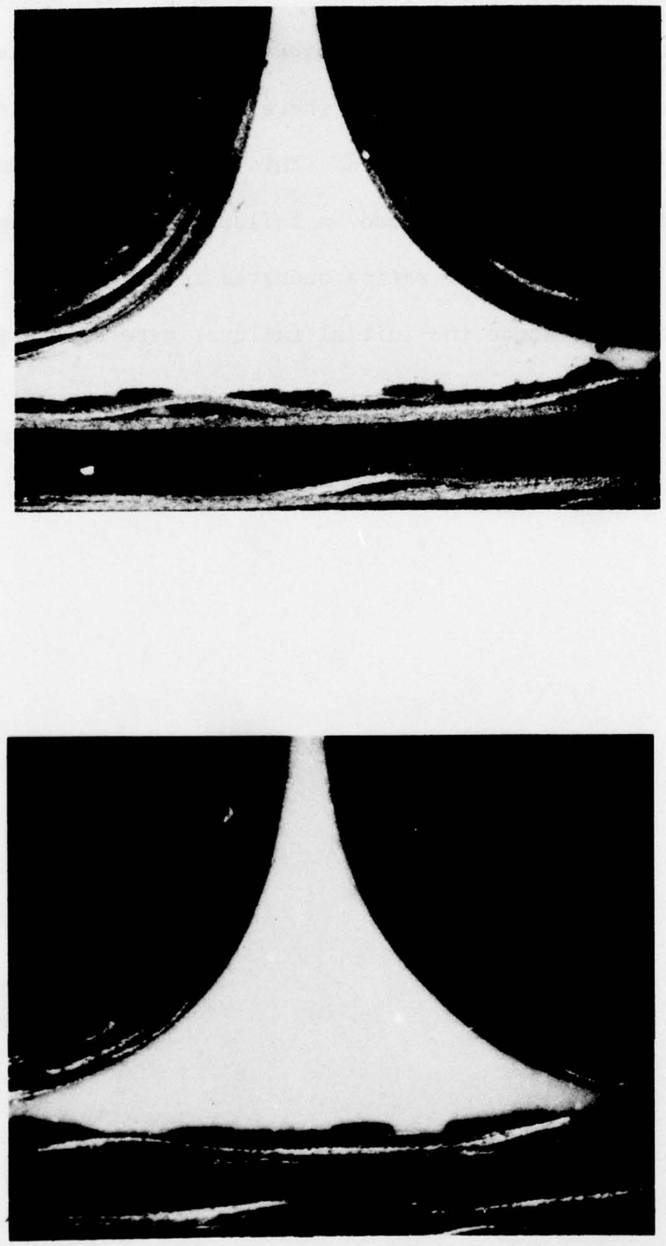


Figure 25. Typical Failed Specimens from Spar 7B

moment conditions was, therefore, not verified by this study. As seen in Table 4, the clamped strength is substantially less than would follow from Reference 5, where the clamped-to-pinned strength ratio of 2.67 is predicted. This can be attributed to the strong effect of the stem load on failure; and would explain the tendency for the smaller ratios observed for the higher strength specimens, where the initial failures were base separations.

VI. TOOLING EVALUATION

Silicone Bladder Shrinkage

An analysis of the tool after the curing of Spar-One indicated that the elastomeric tooling bladders shrank 1/8 in. in the 12 in. (i.e., spar) direction. This contraction (1%) was expected since property data from the manufacturer of the silicone rubber indicated shrinkage of 1% in length for specimens exposed to 350°F. The shrinkage in the 1.5 in. and 4.25 in. directions was also roughly 1%. To insure uniform pressure application, a 0.125 in. aluminum shim was inserted in the 12 in. direction to insure a snug fit of the elastomeric bladders in the metal tool. The shrinkage in the other two directions was considered to be insignificant and no shims were used in these directions. After the initial bladder shrinkage, only small additional rubber shrinkage was noted. This varied from approximately 0.03 in. to 0.01 in. It was not significant since the bladders could easily expand this amount with air pressure.

Bladder Puncture

The puncture repair, accomplished after the cure of Spar-Four (Section V), was successful for the remaining three runs of this program.

Elastomeric Tooling Degradation and Examination

During the 100 psi pressure hold of the cure of Spar-Seven, one of the elastomeric bladders developed a leak. Postcure examination revealed that the metal air entry tube had separated from the elastomeric rubber. This damage was judged to be unrepairable. The elastomeric

tool was cut in half parallel to the 12 in. direction to examine the nature of the disbond between the metal air entry tube and the elastomeric rubber. The air entry tube and its steel collars were found to be totally disbonded. This was attributed to not priming the metal before casting the rubber.

In addition, the wall of the elastomeric tool was observed to have a nonuniform thickness. It tapered from 0.75 in. at the end of the bladder near the air entry parts to 0.50 in. at the opposite end of the bladder. Apparently, when the tool was poured, the weight of the elastomeric rubber was sufficient to compress the polyether/polyurethane foam near the bottom of the bladder. Thus, the walls of the bladder would be expected to be thicker on the bottom and thinner on the top.

Several other interesting features were observed when the bladder was sectioned. The polyether/polyurethane foam which had been covered with the Borden Mystik® tape had been completely charred and all that remained were ashes. A close examination of the inner corners of the elastomeric tool revealed that the elastomeric rubber had seeped into the corners of the polyether/polyurethane foam when the tool was being poured. Thus, the inner corners of the tool were poorly formed and several had small tears in them (Figure 26). These tears could possibly lead to a rupture of the tool at elevated temperature and pressure.

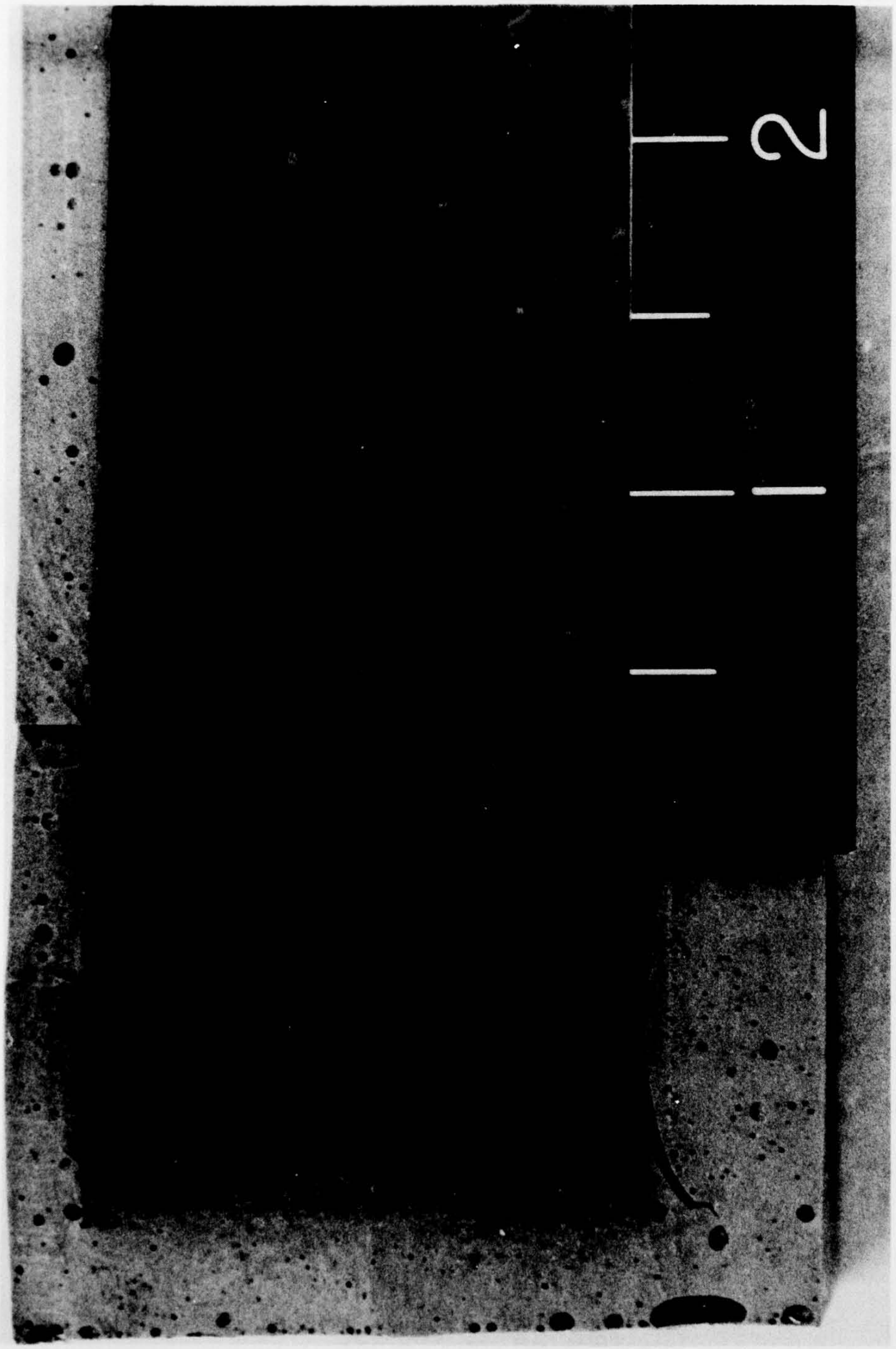


Figure 26. Inner Corner of the Elastomeric Tool

The solid cast rubber section of the tool in which the steel collars of the air entry tube were embedded, was judged to be unnecessarily thick. With proper acid etching and metal priming of the air entry tube and steel collars, the bond between the elastomeric rubber and the air entry tube could be strengthened, and one of the steel collars could be eliminated. This would result in a smaller solid rubber section in the tool which would allow the tool to apply the pressure more uniformly.

Revised Design

The experience gained from the first set of bladders in this program led to a revised bladder design that was successfully applied to numerous fabrication cycles in Reference 3. The primary bladder improvements were as follows:

1. The bladder rubber was changed from Silastic J (high durometer) to the lower stiffness Silastic E.

2. The air entry tube and collar unit was revised to have only two collars (Figure 9). Also, the unit was etched and primed with GE N SS 4004 primer prior to casting in the silicone. Another feature that was added was a split guide block assembly in the aluminum box. This was designed to allow the bladders to be removable from the box without having to cut air tubes to remove the flanged mechanical fittings.

3. Commercial styrofoam blocks were used to form the voids. After initial curing of the silicone rubber, the whole bladder assemblies were cured at 350° for over 4 hours. This procedure preshrinks the rubber and melts the styrofoam into solid resin particles which remain as small pellets inside the bladder.

4. After a premature failure of one of the improved bladders which was fabricated with square corners in the forming blocks, the corners and edges of the styrofoam blocks were rounded (3/8 in. radius) to reduce the chance for corner cracks in the rubber bladder. Also, the bladders were poured to approximately 11 3/4 in. in length. After the bladders were cured, they were cut to size (11 1/2 in.) on a band saw equipped with a knife blade.

Bladders fabricated in this manner were found to last for eight or more 350°F cure runs under 85 to 100 psi. Some of these runs were with the laminate in direct contact with the bladders. These bladders failed in tensile cracks that ran down the 12 in. direction of the inner, vertical side; that is, the long side in contact with the part. Subsequently, direct contact of the silicone rubber with uncured epoxy along the long sides was avoided, by the use of metal cauls.

VII. FINAL PROTOTYPE SPECIMENS

At the conclusion of this screening and tool evaluation program two 12 in. long spars were fabricated to the design of Spar-7B using the Hercules and Fiberite materials described and Section III. The first spar (designated 77-1) is shown in Figure 27 and 28. This spar was oversize and porous due to a bladder failure. Nevertheless, the figures are representative of the visual quality of parts produced with this tooling. The bladder failure was caused by cracks in the corners, as discussed in Section VI. This was the first bladder formed with styrofoam and Silastic E rubber, and the corners of the blocks were sharp. A new set of bladders was prepared to the improved design of Section VI with rounded corners on the styrofoam blocks and used to prepare another spar. This spar was designated 77-2. It was initially prebled for 20 minutes at 200°F and 29 in vacuum. After cure, the spar was inspected by coin tap and ultrasonic C-scan and appeared well compacted. Thicknesses were uniform, but about 7% less than estimated using the same estimate bases given in the notes of Table 2. Therefore, these specimens may have been slightly resin lean.

Specimens from this spar were tested in flatwise tension/simple support loading (pinned test fixture with a 2.67 in. span). Data, shown in Table 8, indicate the weaknesses of edge specimens (77-2-1 and 10). The average strength of this spar is 14% less than that achieved for

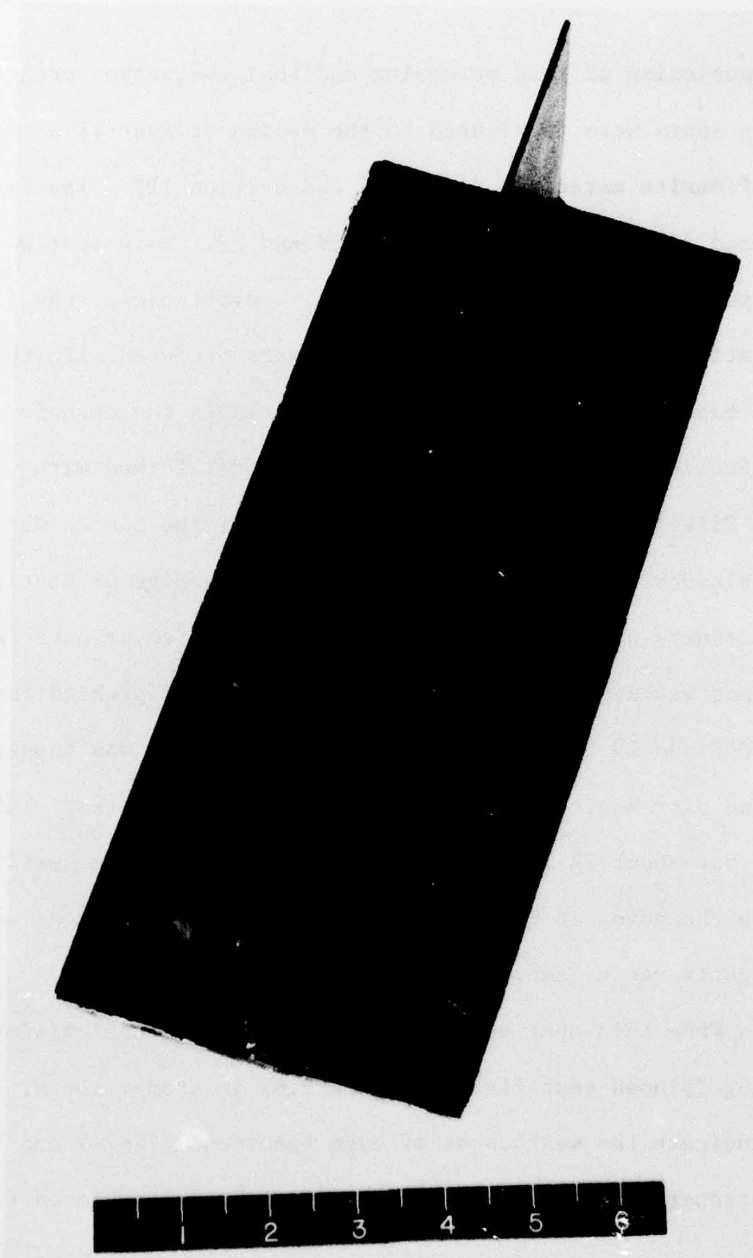


Figure 27. Cured Spar as Removed from the Tool

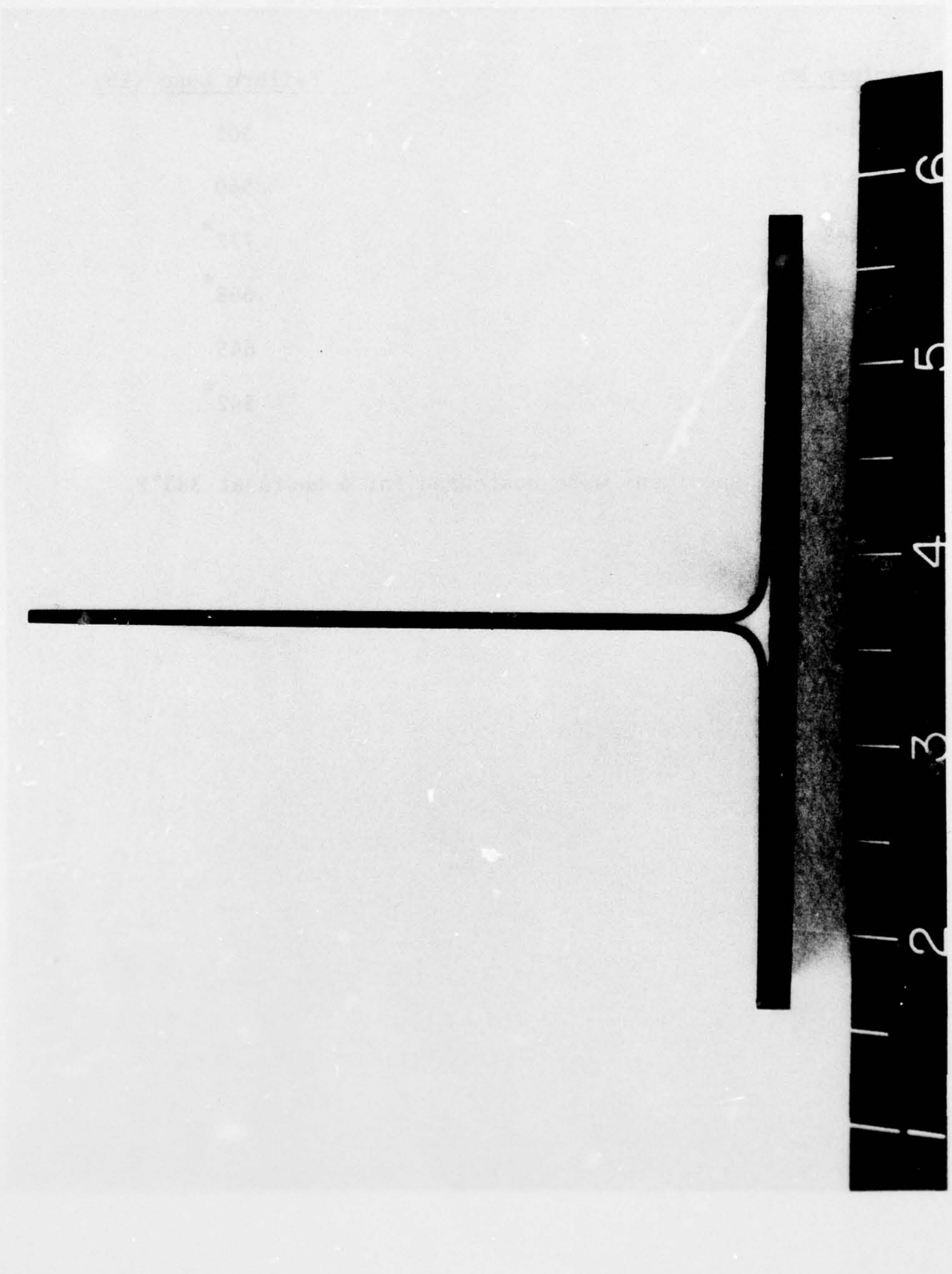


Figure 28. Edge View of a Typical Spar

TABLE 8

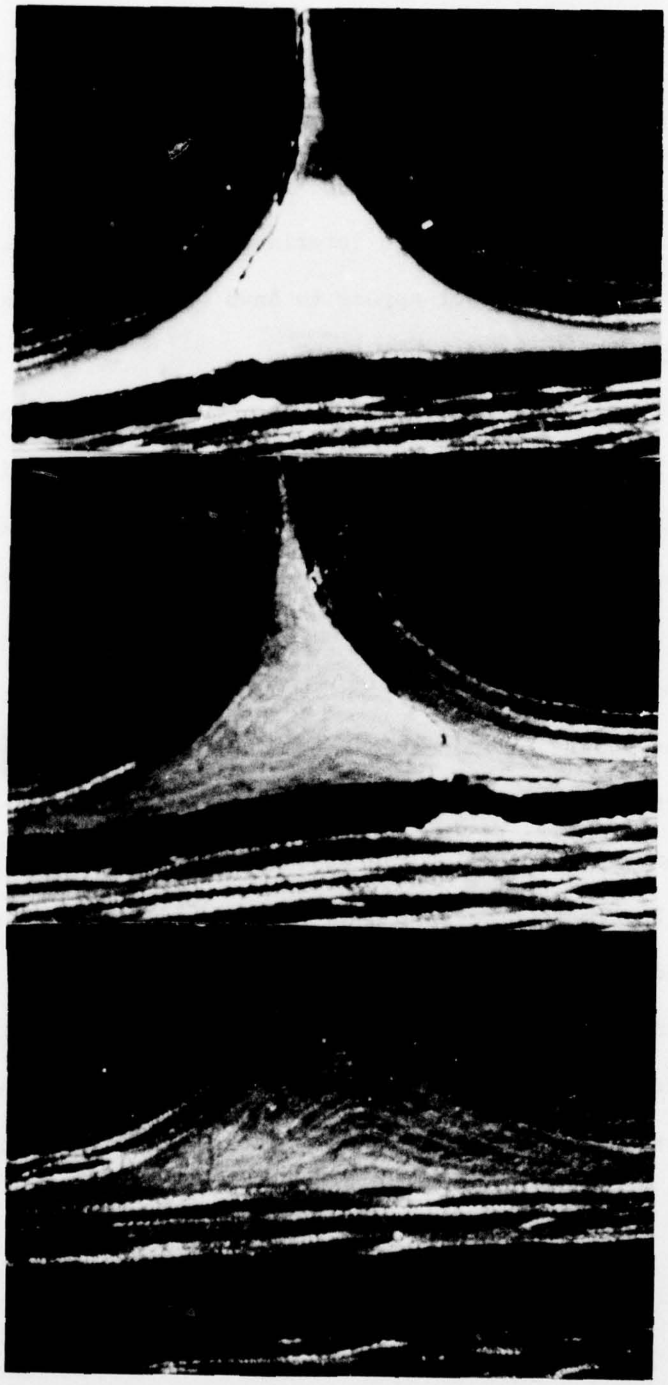
FAILURE LOADS OF SPECIMENS FROM SPAR-77-2

Specimen No	Failure Load (lb)
77-2-1	505
77-2-2	560
77-2-3	772*
77-2-8	668*
77-2-9	645
77-2-10	542*

NOTE: *These specimens were postcured for 4 hours at 385°F.

Spar-7B. It, therefore, appears that the resin rich nature of Spar-7B may have aided its interlaminar tensile strength. Also, the age of the material used for the baseline specimens of this program does not appear to have been detrimental to interlaminar strength. As shown in Table 8, postcuring did not appear to have altered the flatwise tensile strength of the specimens.

Failure modes for these specimens were comparable to those for Spar-7B, with failures initiating in the base plies, followed by secondary failures in the stem fillets. Some specimens (Figure 29) indicated a vertical crack in their root filler (occurring after the main failure). Close examination revealed a reduced cross section of adhesive/scrim along these cracks, which was caused by laminate resin moving into the root. An indication of this is seen in the upper root vertex of specimen 77-2-2. After sectioning, this laminate resin zone was found to extend over 1/2 of the root height, thus producing a zone of weakness. Specimens from this spar were the only cases where major cracks appeared well within the adhesive/scrim root filler. As a parenthetical note, over 100 specimens, tested in Reference 3, showed no such root cracks. Thus, the findings of this study relative to a practical, inexpensive root filler were subsequently demonstrated to be correct.



Specimen
77-2-2

Specimen
77-2-3

Specimen
77-2-10

Figure 29. Fracture Modes for Spar-77-2

VIII. CONCLUSIONS

1. The elastomeric bladder or controlled pressure elastomeric tool is a practical and inexpensive method of producing "T" structural shapes from advanced composites. It is particularly valuable for use in fabricating small numbers of these specimens for the screening of root areas and developing data on failure modes.

2. The root area of "T" specimens, representative of the spar to wing-cover intersection in an aircraft wing with integral fuel tank should be filled with a material that has transverse strength. A rolled laminate of film adhesive and glass cloth provides this strength and is practical in the fabrication of components.

3. Adhesive layers should be extended from the root between (a) the stem halves, and (b) between the stem plies that form the upper layers of the base (wing cover) and the lower section of the base. A one inch extension from each root vertex is considered appropriate, although this design should be explored further.

4. Woven material proved to be labor saving and a practical means to screen root concepts and verify tooling.

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